Final Research Report
Efficiency of Standard Stormwater Best Management Practices for Nitrogen Removal
Project # 2009-9152

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1. Abstract

Management plans call for a 10% reduction in nonpoint runoff of nitrogen (N) from Connecticut stormwater, as part of an effort to combat hypoxia in Long Island Sound (LIS). Stormwater ponds and other structural BMPs (best management practices) are being widely implemented in an effort to reduce nitrogen loading. We examined the effectiveness of wet ponds and wetlands (hereafter, ponds) in removing nitrogen from stormwater. We also investigated the spatio-temporal variability in stormwater nitrogen concentrations, in order to understand whether nitrogen loading can best be controlled by targeting specific high-nitrogen stormwater sites for BMP implementation.

We found that 4 out of the 7 stormwater ponds studied displayed statistically significant N removal. Overall N removal at these 4 sites was around 35%. However, N removal efficiency at these sites was high when stormwater N concentrations were high, and was much lower or non-existent when concentrations were low. Similarly, the 3 sites where no N removal was occurring were sites with relatively low influent N concentrations. Both of these results support our hypothesis that stormwater BMPs are effective when influent concentrations are high, but not when they are low. However, we found the "irreducible concentration" (the concentration below which there is minimal removal) to be lower than in previous studies, at approximately 1 mg/L total nitrogen.

Our analysis of an existing Connecticut stormwater database showed that median total nitrogen (TN) concentrations in Connecticut stormwater are ~1.6 mg/L, but there are sites with significantly higher concentrations (Kruskal-Wallis test, $p<0.001$). Our calculations suggest that a 10% reduction in total stormwater N runoff could potentially be achieved by implementing BMPs for 15% of total stormwater sites – provided that these 15% are the sites with the highest N concentrations. However, our supplemental sample collection suggested that the existing database underestimates the temporal variability in stormwater N concentrations, which may substantially affect our conclusions on the role of high-nitrogen sites.

2. Introduction

Excess nitrogen loading, resulting in summertime hypoxia, has been identified as a priority problem facing Long Island Sound (Long Island Sound Study 1994). Sources of nitrogen (N) to LIS include sewage treatment plants and runoff from urban, agricultural, and forested landscapes (NYSDEC/CTDEP 2000).

Management plans for reducing nitrogen loading to LIS have called for a 10% reduction in nonpoint (runoff) sources of N in CT and NY (NYSDEC/CTDEP 2000). In the face of continuing development pressures, meeting these targets will require both smarter growth and implementation of stormwater best management practices (BMPs) in new and existing urban areas.

Stormwater BMPs are being widely implemented in CT and throughout the country in an effort to alleviate stormwater peaks and reduce pollutant loading to waterways. Typical structural BMPs include wet ponds, wetlands, dry ponds, infiltration trenches, etc. However, it is still unclear whether these stormwater BMPs are capable of reducing nitrogen loads to the extent required. This project aims to assess the efficiency of BMPs in CT and evaluate whether they can provide substantial reductions in nitrogen loads. This will assist managers in deciding whether (and where) to implement BMPs as nitrogen reduction tools.

Our research focuses on wet ponds and wetlands, which appear to show the greatest likelihood of reducing N loads. Wet ponds and wetlands can potentially capture nitrogen in several ways:

- sedimentation of particulate forms of nitrogen;
- uptake of soluble nitrogen by aquatic or wetland plants (ultimately leading to nitrogen burial in sediment);
- denitrification of NO_3 (leading to loss as N_2 gas).

Two groups have attempted to compile the available monitoring data on structural BMPs. The Center for Watershed Protection's National Pollutant Removal Performance Database (Winer 2000, CWP 2007, and http://www.stormwatercenter.net) was updated in September 2007 and included 166 studies, of which only 2 are from Connecticut (a wet pond study from 1989 and a rain garden study from 2006). The International Stormwater BMP Database (US EPA 2002, WERF et al. 2007, and http://www.bmpdatabase.org) contains only one study from CT (a 1999 study of a Vortechs system). There is thus a paucity of information on the effectiveness of stormwater BMPs in CT.

The two groups mentioned above have used their compilations of the available studies to assess the effectiveness of different BMPs in removing a variety of pollutants. The Center for Watershed Protection has found a very large range in percent removal for total nitrogen (TN) and NO_3 for both wet ponds and wetlands (Table 1). The International Stormwater BMP Database has argued against percent removal as a metric, and instead has examined the statistical significance of the differences between influent and effluent concentrations. They have found that wet ponds did lead to a statistically significant reduction in NO_3 and TN concentrations, but wetlands did not (Table 2).

Table 1. BMP effectiveness as compiled by the Center for Watershed Protection (2007)

BMP type	Number of studies	Median TN removal	Minimum TN removal	Maximum TN removal
wet pond	22	31%	-12%	76%
wetland	24	24%	-49%	76%

Table 2. BMP effectiveness as compiled by the International Stormwater BMP Database (WERF et al. 2007)

BMP type	Number of studies	Statistically significant TN removal?	Median effluent TN concentration (mg-N/L)
wet pond	20	yes	1.31
wetland	7	no	1.15

Schueler (2000) has argued that effluents from structural BMPs appear to have an "irreducible concentration," that is, a lower-limit effluent pollutant concentration that can't be decreased even by increasing BMP size or treatment time. This implies that for influent stormwater concentrations that are relatively low (not much above the irreducible concentration), pollutant removal will be low or non-existent. Schueler's estimates of the irreducible concentrations of TN and NO_3 from wet ponds and stormwater wetlands are shown in Table 3; the effluent data in

Table 2 serve as independent estimates of the irreducible concentrations. It appears from these data that these structural BMPs cannot be expected to reduce TN concentrations below ~1.2-1.9 mg/L.

Table 3. Irreducible concentrations, as compiled by Schueler (2000)

BMP type	Number of studies	Mean effluent TN concentration (mg-N/L)	Mean effluent NO_3 concentration (mg-N/L)
wet pond	11	1.91	0.70
wetland	11	1.63	0.35

Preliminary analysis of stormwater data compiled by CT DEP suggests a median TN concentration of 2 mg/L. If it is really true that untreated stormwater in CT has N concentrations only slightly above the irreducible concentrations, managers should not expect structural BMPs to provide much nitrogen removal. However, this median may mask considerable site-to-site variability. Could stormwater BMPs targeted towards the more polluted sites be used to provide considerable N removal?

This research was designed to help improve stormwater management in Connecticut by testing the following three hypotheses:

H_1: Untreated municipal stormwater in Connecticut generally has relatively low TN concentrations of ~2 mg/L, but a substantial fraction of sites have higher concentrations.
H_2: Stormwater BMPs in Connecticut (specifically wet ponds) are able to achieve statistically significant reductions in TN loads when influent concentrations are high, but not when they are low.
H_3: The target of 10% reduction in stormwater TN loads can be achieved by selective application of BMPs to the most polluted sites.

3. Methods

3.1. Stormwater N Concentrations in Connecticut

We collected data on stormwater nitrogen concentrations from two sources: the MS4 database and our own sampling.

3.1.1. MS4 Database

We obtained and analyzed CT DEP's database on municipal stormwater, which consists of data from municipal monitoring of MS4s (municipal separate storm sewer systems), required by the stormwater general permit. The database, as received from DEP, consisted of 2462 entries collected by 106 towns over the period 2004-2008. We eliminated duplicate entries (same date, same site, same concentrations) and averaged replicate values (same date, same site, different concentrations), which reduced the database to 2443 unique samples. The nature of the data is highly variable from town to town: some towns collected annual samples consistently at the same sites over the entire 5 year period, while data for other towns consist of samples from only one year, or samples from different sites each year.

We wanted to identify those sites that had been sampled repeatedly and had enough data to provide a reasonable sense of conditions. To do this, we manually sorted through the database and assigned each sample location a unique identification number. In cases where the location description in the spreadsheet did not allow us to determine whether two samples were from the same site, we made our best guess, erring on the side of not assuming that samples were from the same site. This resulted in a total of 831 different sample sites, with the number of samples per site ranging from 1 to 5 (Table 4). Of the 237 sites that had been sampled 5 times each, 16 sites had incomplete data for NO_3 and/or TN, leaving 221 sites with complete data for all 5 years; these were the primary focus of our analysis.

Table 4. Sites in the MS4 database grouped by number of samples per site

number of samples per site	**number of sites**
1	270
2	97
3	114
4	113
5	237
TOTAL	831

For these 221 sites, we calculated median concentrations of NO_3 and total N[1] and carried out a Kruskal-Wallis test to determine whether there were differences in the medians by site. We also calculated cumulative nitrogen loads from groups of sites, starting with the highest-concentration site and proceeding through the dataset. For this process, we assumed that each site represented an equal annual volume of stormwater, i.e., that all sites had equal flows.

3.1.2. Stormwater Sampling

We supplemented the MS4 database by collecting new samples during 4 rain events from 12 sites in New Haven and Seymour.[2] These sites were selected because they met the following criteria:

- they were sites previously sampled by the municipalities
- we were able to identify and locate the exact sample locations (based on conversations with municipal officials)
- some of these sites showed signs (based on preliminary examination of the MS4 database) of being unusually high in nitrogen
- the sites were near enough to each other and to our labs that we were able to sample them while stormwater was flowing during rain events.

Figure 1 presents a map of the sites, and Table 5 summarizes the locations and dates sampled. Combining our data with the data from the MS4 database for these sites resulted in a sample size of 8 for each site except Essex, which had a sample size of 7.

[1] The database included data on NH3, NO3+NO2, and TKN (total Kjeldahl nitrogen), along with other, non-nitrogenous pollutants. We assume that the amount of NO2 was insignificant, so we refer to NO3+NO2 as NO3 (and assume it is comparable with our ion chromatography measurements of NO3). We calculated total N as the sum of NO3+NO2 and TKN.

[2] Not all sites were sampled during all events; see Table 5.

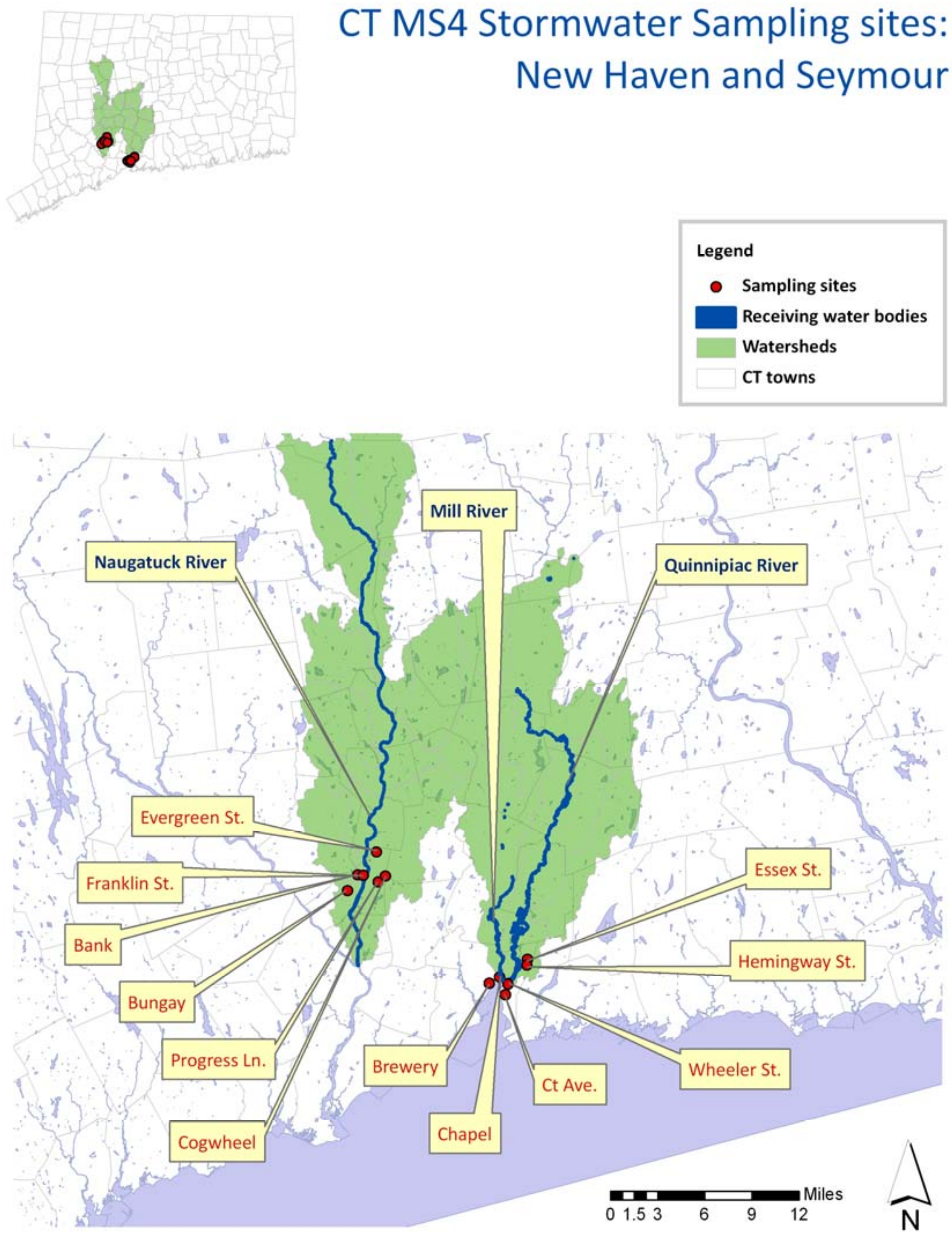


Figure 1. Map of stormwater sampling sites.

Samples were collected by hand and stored on ice until return to the laboratory. Samples were filtered in the lab (0.45 μm filter), and both filtered and raw samples were frozen for later analysis. Frozen samples were fully thawed before analysis. Cl, NO_3, PO_4, and SO_4 were measured on filtered samples using a Dionex ion chromatograph. Where concentrations of NO_3 were below the detection limit (0.01 mg NO_3-N/L), we used a value of half the detection limit. Total N (TN) and total P (TP) were measured on raw samples by alkaline persulfate digestion followed by detection of NO_3 and PO_4 on an Alpkem flow analyzer.

Table 5. Locations and dates of stormwater sampling for this project

Site name	Municipality	Type	Latitude	Longitude	Dates sampled
Brewery	New Haven	catchbasin	41.39706071	-73.08148560	11/9/09, 1/25/10, 2/24/10, 3/29/10
Chapel	New Haven	outfall	41.30350233	-72.90770939	11/9/09, 1/25/10, 2/24/10, 3/29/10
CT Ave	New Haven	catchbasin	41.28721671	-72.90065476	11/9/09, 1/25/10, 2/24/10, 3/29/10
Essex	New Haven	catchbasin	41.31966591	-72.87357425	11/9/09, 1/25/10, 2/24/10, 3/29/10
Hemingway	New Haven	catchbasin	41.31439378	-72.87410441	11/9/09, 1/25/10, 2/24/10, 3/29/10
Wheeler	New Haven	catchbasin	41.29694693	-72.89742379	11/9/09, 1/25/10, 2/24/10, 3/29/10
Bank	Seymour	outfall	41.39706071	-73.08148560	1/25/10, 2/24/10, 3/29/10
Bungay	Seymour	outfall	41.38242097	-73.09422769	1/25/10, 2/24/10, 3/29/10
Cogwheel	Seymour	outfall	41.39602186	-73.04772070	1/25/10, 2/24/10, 3/29/10
Evergreen	Seymour	outfall	41.41813098	-73.05843403	1/25/10, 2/24/10, 3/29/10
Franklin	Seymour	outfall	41.39687564	-73.07481310	1/25/10, 2/24/10, 3/29/10
Progress	Seymour	outfall	41.39046592	-73.05659462	1/25/10, 2/24/10, 3/29/10

3.2. N Removal Efficiency of Stormwater Ponds

3.2.1. Site Selection

No centralized database exists on stormwater ponds and wetlands in CT.[3] We compiled information on the locations of these sites through several approaches:

- We contacted municipal officials (Town Engineers, Planning and Zoning officers, and/or Inland Wetlands officers) in Branford, Berlin, Bethany, Cheshire, Cromwell, Durham, East Haven, East Hampton, Guilford, Hamden, Hartford, Madison, Meriden, Middletown, New Haven, North Branford, North Haven, Orange, Plainville, Portland, Southington, and Woodbridge. We visited town halls, spoke with many knowledgeable and helpful municipal employees, and examined records.
- The South Central Connecticut Regional Water Authority (RWA) provided us with information on stormwater BMPs that they have commissioned in the Lake Whitney watershed (Hamden and New Haven).
- Milone and MacBroom shared with us information on stormwater ponds that they have designed and installed throughout Connecticut.

[3] The Connecticut Low Impact Development Database, at http://clear.uconn.edu/tools/lid/index.htm, has only one stormwater wetland site listed.

Based on these contacts, we compiled an initial list of approximately 60 sites, out of which we visited (often accompanied by local officials) 36 sites in Branford, Cheshire, Hamden, Orange, Portland, and Woodbridge. From these, we selected 8 final sites based on criteria of: accessibility; similarity in size, shape, and hydrology; and the likelihood of covering a range of influent nitrogen concentrations.

3.2.2. Site Descriptions

The selected study sites are described in this section. A map outlining the study sites is included in Figure 2, and basic site parameters are summarized in Table 6.

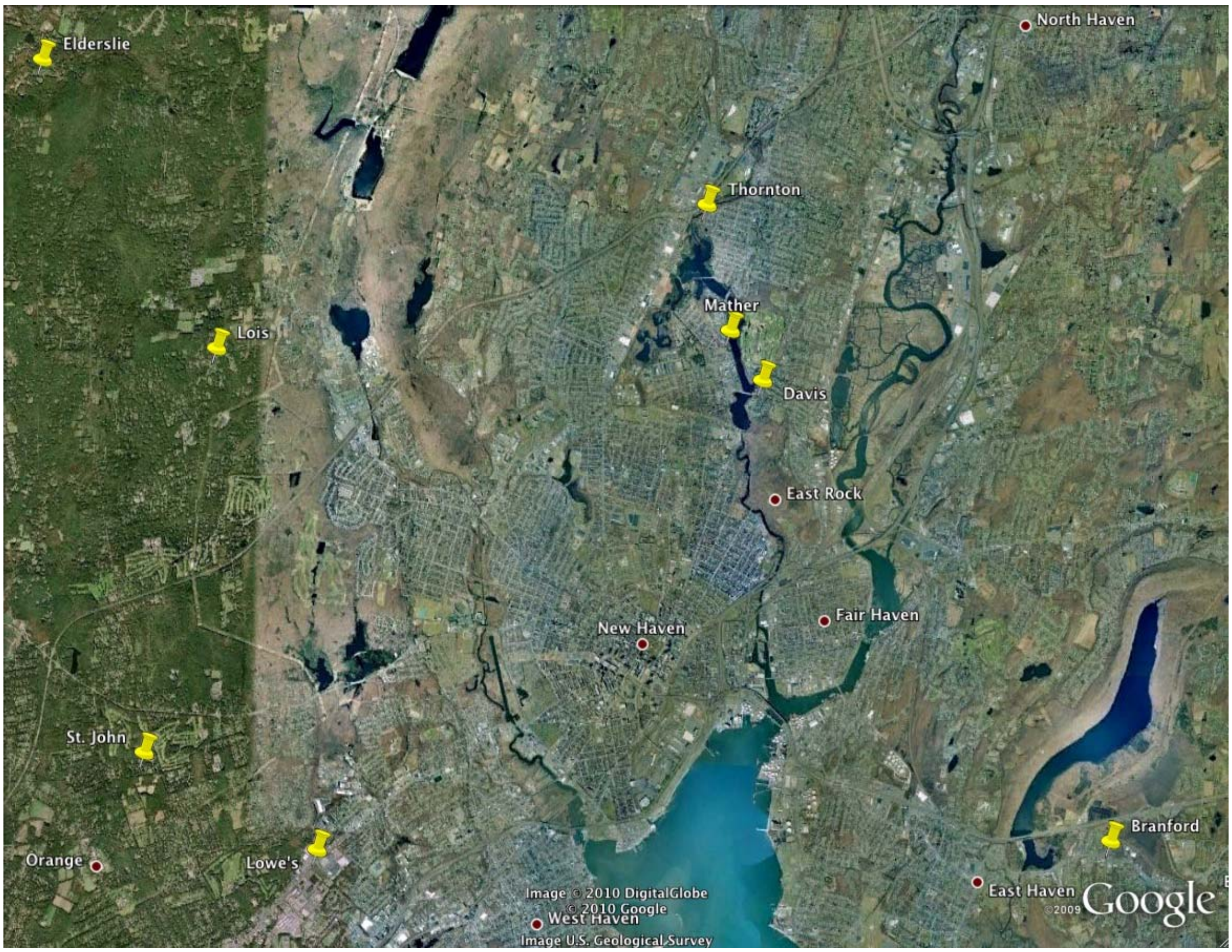


Figure 2. Map of stormwater ponds sampled. Image from Google Earth.

Our 8 sites straddle the line between *wet pond* and *wetland* – a line that, in our opinion, is often drawn too sharply. All of the sites retain pools of standing water between storms, and all but one have significant vegetation (partly in standing water and partly in saturated soils), with the mix of open water and vegetation differing from site to site but also seasonally. For simplicity, we refer to them all as ponds.

Table 6. Stormwater ponds sampled in this project

Site Name	Address	# Bays	# Inlets	# Outlets	Lining	Vegetation
Branford	515 West Main Street, Branford, CT, 06405	1	1	1	Soil	Yes
Davis	Hartford Turnpike & Davis Street, Hamden, CT 06517	3	1	1	Soil	Outlet pond only
Elderslie	Elderslie Lane, Woodbridge, CT 06525	1	1	1	Rock	Yes
Lois	Lois Drive Woodbridge, CT 06525	1	1	1	Soil	Yes
Lowes	50 Boston Post Road, Orange, CT 06477	2	1	1	Soil	Yes
Mather	Whitney Avenue & Mather Street, Hamden, CT 06517	3	1	1	Soil	Outlet pond only
St. John	St. John Drive, Orange, CT 06477	1	2	1	Soil	Yes
Thornton	Thornton Street, Hamden, CT 06517	1	1	1	Soil	No

Branford

This is a commercial site located behind a Honda dealership. Stormwater drains from the parking lot surrounding the building and flows to the wet pond; the inlet and outlet are at opposite ends of the pond. Vegetation occupies the surface of the pond.

Davis

This site is in a residential area adjacent to Lake Whitney. It is owned by the RWA. Stormwater drains to the pond from Hartford Turnpike. The pond contains 3 separate bays, all separated by weir boards: an inlet bay, a large side overflow bay, and an outlet bay. There is one concrete culvert inlet at the inlet bay, and one weir box outlet near the outlet bay. There is no vegetation in the inlet and side bay. There is some vegetation in the outlet bay.

Elderslie

This site is located in a residential area; it is at the end of a cul-de-sac in a recently constructed housing development. Stormwater drains from the street, which slopes downward and reaches its lowest point at the location of the wet pond. The pond failed in its first iteration, and was redesigned to better accommodate runoff. The pond has one concrete culvert inlet and one stormwater box outlet at opposite ends of the pond. The pond is lined with large stone cobbles, as opposed to soil substrate. Vegetation extends across the surface of the pond.

Lois

This is a residential site; it is located behind two houses in a small housing development. Stormwater drains from the street, and the pond is set back at a lower elevation adjacent to a stand of trees. The wall of the pond is lined with cobbles, while the bed is soil substrate. The pond has one plastic culvert inlet and one stormwater box outlet at opposite ends of the pond. There is a string of cobbles that creates a smaller bay within the larger pond. The pond is filled with vegetation.

Lowes

This is a commercial site located in a Lowes parking lot. The pond is situated on a grassy embankment and consists of two bays, an upper and a lower; there is a substantial decline in elevation from the inlet to the outlet. Stormwater drains from the parking lot to the upper bay through a large plastic culvert inlet, flows through another culvert and pours into the lower bay, and exits the pond through a small plastic culvert. The pond is filled with vegetation, which was cut to the ground by maintenance crews part way through the study.

Mather

This RWA site is located in the vicinity of a dense urban area. It located between Lake Whitney and Whitney Avenue. Stormwater drains from Whitney Avenue and enter the stream through a plastic culvert. The pond consists of 3 bays, the first two of which may sometimes be dry. Stormwater passes in a zigzag pattern through the 3 bays and exits through a weir stormwater box. There is also an overflow culvert that runs between the first pond and the outlet stormwater box. Forested area immediately surrounds the pond. The pond has sparse vegetation in the third bay.

St. John

This is a residential site located across the street from a single family home, and is adjacent to a site where a housing development is being constructed. Stormwater drains to the pond from St. John Drive. Water enters the pond through two separate concrete culvert inlets; they are located on opposite ends of the pond. Stormwater passes through a ring of cobbles and infiltrates a bed of gravel to enter a concrete outlet stormwater box. The pond does not always have significant standing water within it; often the pond bed merely remains waterlogged. Short vegetation covers the pond. Toward the end of the study, heavy construction activity was taking place near the pond.

Thornton

This RWA site is located in a residential area. The site is also identified as “Johnson’s Pond” by the RWA. The pond is set back from the street in a wooded area, and is located within the vicinity of several houses. Water enters the system through a black plastic culvert, and exits through a weir box. This pond drains rapidly and may often be dry between storms. The bed is a soil substrate, and is dotted with vegetation at the edges.

3.2.3. Sampling Methods

At each site, one Global Water WL-16 water level logger was installed in the main pond and used to record water level in the pond at 5 minute intervals throughout the study period of June through December 2009. Batteries were replaced and data were downloaded at approximately monthly intervals. Equipment malfunction led to some missing data.

During the study period, a total of 21 individual storm events were sampled (Table 7), though not all sites were sampled during all events. With the exception of the “autosampler storms” (see below), sampling was done manually at 1-4 points in time over the course of each event, depending on the number of people available for sampling and the number of sites being sampled. Table 7 summarizes the samples collected.

At each sampling time, water samples were collected at both the inlet and the outlet. Samples were stored on ice and promptly brought to the laboratory, where both filtered and raw samples were frozen for later analysis as described in Section 3.1.2. In addition, turbidity was measured in the field in duplicate using a LaMotte 2020 turbidimeter. On occasion, samples were also collected in a sterile bottle, and analyzed for *E. coli* levels using the IDEXX Colilert system. Only Cl, NO_3, and TN data are analyzed in this report, although all the original data are provided in the accompanying database.

Table 7. Summary of stormwater pond sampling: number of sample times for each storm at each site. Empty cells indicate the site was not sampled for the given storm. AS = autosampler.

	Branford	Davis	Elderslie	Lois	Lowes	Mather	St. John	Thornton
6/3/09		1	1	1	1			
6/5/09		3	3	3	3	1	3	
6/10/09		4						
6/14/09		4						
6/19/09		1	1	1	1	1	1	
6/21/09		2	1	1	1	2	1	
6/25/09		3	2	2	2	2	2	
6/27/09		1	1	1		1	1	
7/1/09		1						
7/7/09		2	1	1	1	2	1	
7/22/09	2	2	2	2	2	2	2	2
7/24/09		3	2	2	2	2	2	2
7/30/09		1	1	1	1	1	1	1
8/22/09		1				1		
8/29/09	2	3	2	2	2	2	2	2
9/12/09	1	2	2	2	2	1	2	2
9/27/09		4	3	3	3	4	3	4
11/14/09		4	2	3	2	4	2	4
11/20/09				24 (AS)				
11/30/09		3	2	24 (AS)	2	3	2	3
12/2/09				24 (AS)				
TOTAL	5	46	26	97	25	29	25	20

In order to provide a more detailed look at stormwater chemistry over the course of a storm event, ISCO autosamplers were used to capture three storm events during the later portion of the study. Two autosamplers were placed at the Lois site, with one at the inlet and one at the outlet. For each storm event, 24 samples were taken: one every half-hour over the course of 12 hours. On occasion, a full 24 samples were not taken by one of the autosamplers, due to equipment malfunction.

Figure 3 highlights our sampling dates for both the stormwater sampling and the BMP/pond sampling, and places them in the context of the precipitation record for this time period. As can be seen, we were able to sample a significant fraction of the important precipitation events over the period of study.

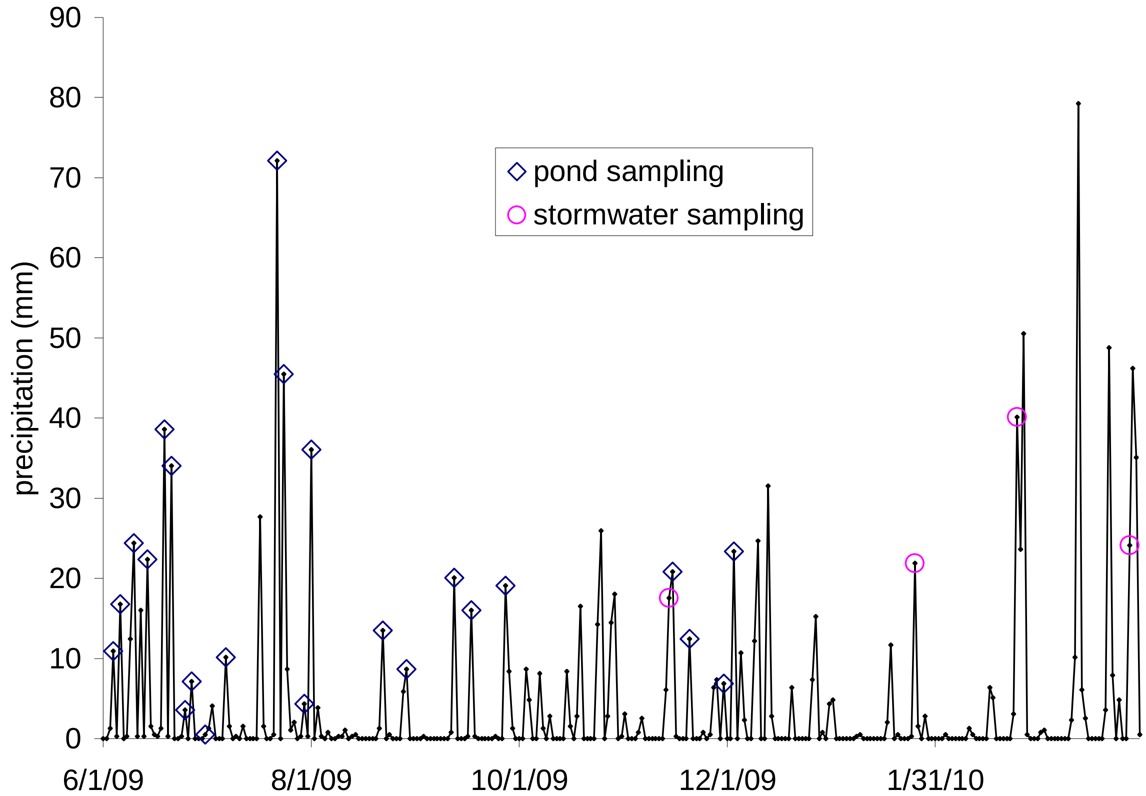


Figure 3. Daily precipitation (6/1/09-4/1/10) with sample dates indicated. Stormwater sampling (Table 5) took place on the dates indicated by circles. Pond sampling (Tables 6 and 7) took place during the <u>storms</u> indicated with diamonds, but often stretched over more than one day. Data source: NOAA National Climate Data Center, station 72504514758, available from http://cdo.ncdc.noaa.gov/CDO/dataproduct

3.2.4. Analysis

We used the "Recommended Method" of US EPA (2002) for assessing BMP efficiency. For each storm event, an event mean concentration (EMC) was calculated for influent and effluent at each site, as the mean of all data available for that location. For St. John, the concentrations at the two inlets were averaged to calculate an influent EMC.

EMCs were generally not normally distributed, so statistical analysis was carried out on log-transformed data. Paired t-tests were carried out comparing (log-transformed) influent and effluent EMCs. Where data were not normally distributed even after log transformation, a Wilcoxon Signed Rank test was carried out instead. Probability plots of log-transformed influent and effluent data (with best-fit lines) were used to assess whether removal efficiency was concentration-dependent (US EPA 2002). For comparison, probability plots and paired t-tests were prepared for the conservative tracer Cl as well as for NO_3 and TN.

We also calculated percent removal for each site for each storm event using equation 1. We then calculated the overall removal for each site as the weighted average of the removals for individual storm events, where each event was weighted by the amount of precipitation recorded during that event at Tweed New Haven Airport (National Climate Data Center station number 725045).

$$removal(\%) = \frac{EMC_{IN} - EMC_{OUT}}{EMC_{IN}} \qquad \text{equation 1}$$

3.3. Quality Control

Quality control (QC) measures, including field and lab replicates, lab blanks, spikes, and laboratory reference materials, were utilized throughout the project. QC results (Table 8) demonstrate that data collected for this project is of high quality.

Table 8. Quality control measures for laboratory analyses. n = number of samples

		Cl	NO_3	TN
field replicates	**n**	15	15	15
	average CV	5.2%	9.8%	9.5%
lab replicates	**n**	41	41	30
	average CV	0.9%	1.7%	3.8%
field blanks	**QC goal**	<0.1 mg/L	<0.01 mg/L	<0.05 mg/L
	n	9	9	10
	n meeting goal	9	8	9
spikes	**QC goal**			85-115%
	n			13
	n meeting goal			10
reference materials	**QC goal**	90-110%	90-110%	90-110%
	n	21	21	16
	n meeting goal	21	21	16

4. Results

4.1 Stormwater N Concentrations in Connecticut

4.1.1. MS4 Database

Median NO_3 and TN concentrations in the MS4 database were approximately 0.5 and 1.6 mg/L, respectively. However, these medians mask a great deal of variability, as illustrated by the box plots shown in Figure 4. When median concentrations were calculated for the 221 sites with 5 sample points each, these concentrations spanned a range from 0.03-6.3 mg/L NO_3-N (median =0.47) and 0.41-7.2 mg/L TN (median = 1.6). The Kruskal-Wallis test indicated that there were significant differences by site in concentrations of both NO_3 and TN ($p<0.001$).

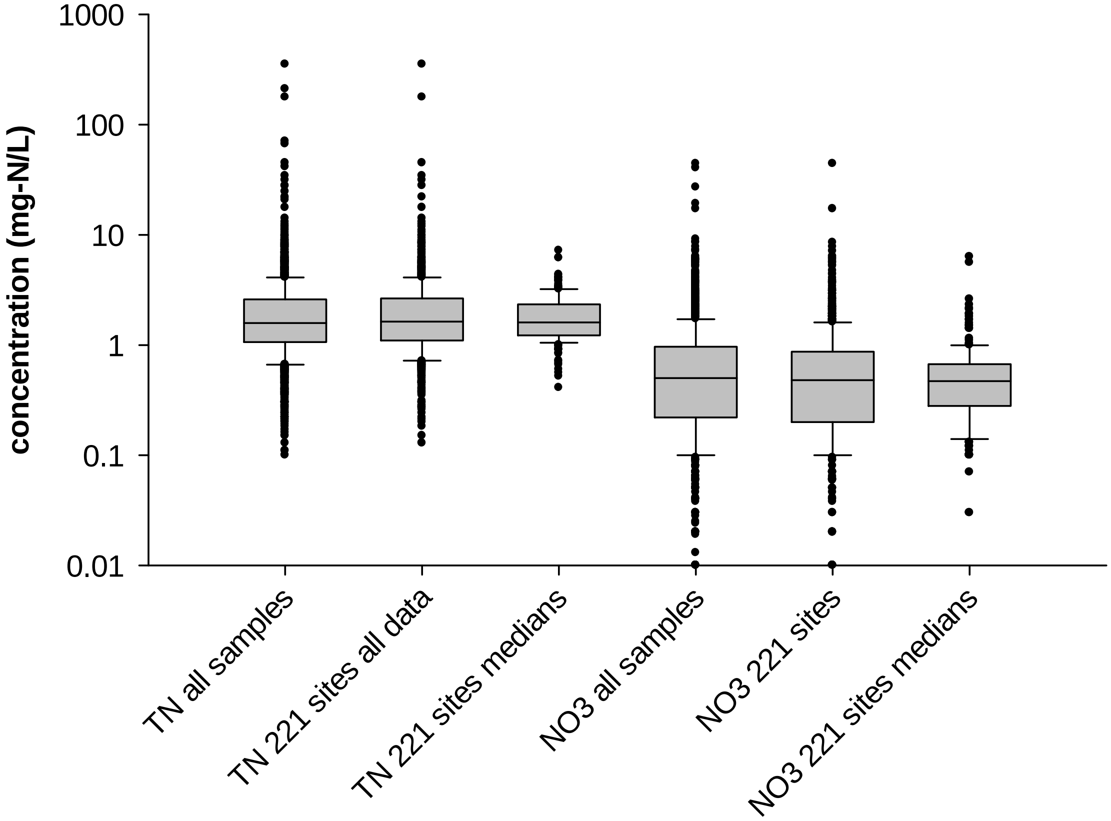


Figure 4. Box plots of TN and NO_3 concentrations from the MS4 database: all data (n=2443), only data from the 221 sites with 5 samples each (n=1105), and site medians for the 221 sites with 5 samples each (n=221). Shown are 10^{th}, 25^{th}, 50^{th}, 75^{th}, and 90^{th} percentiles, and all points outside 10^{th}-90^{th} percentiles.

Because of this variability in nitrogen concentrations, the most polluted sites account for a disproportionate fraction of the stormwater nitrogen load, as illustrated in Figure 5. Thus, for example, 20% of the TN load is contributed by the top 9% of sites (Figure 5). The pattern is even more dramatic for NO_3, where 20% of the load is contributed by 4% of sites. This suggests an opportunity for achieving significant N reductions by targeting stormwater BMPs at the most polluted sites.

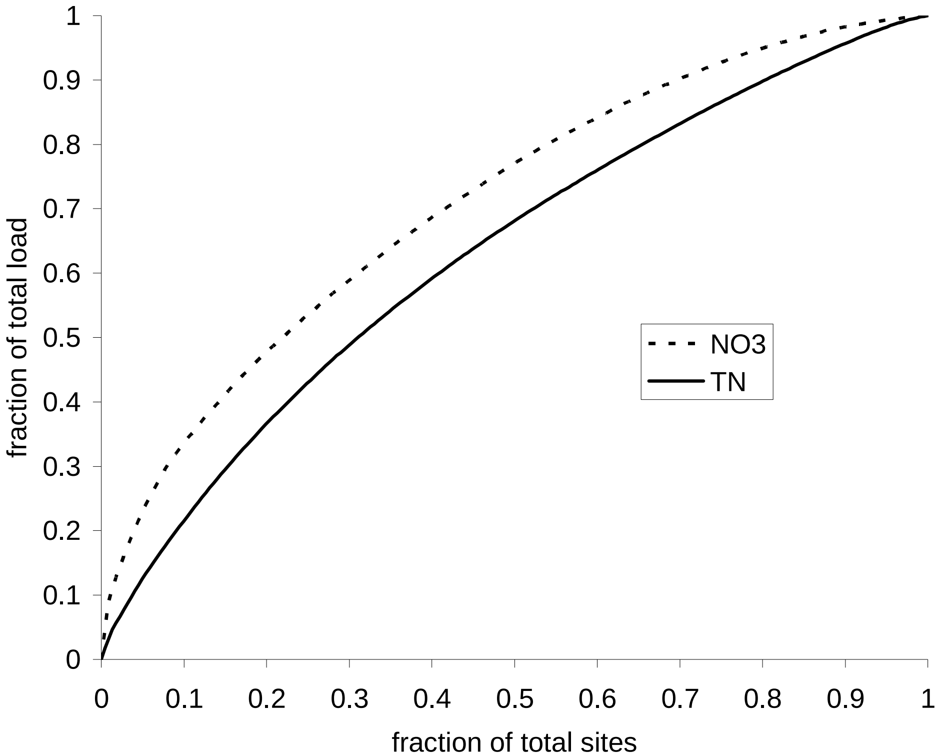


Figure 5. Fraction of total nitrogen load as a function of the fraction of total sites, based on the 221 sites from the MS4 database with 5 samples each. Calculated based on a list of the 221 sites ordered by median concentration (highest to lowest).

4.1.2. Stormwater Sampling

Total N concentrations for the 12 sites sampled (including both our data and previous municipal data) are shown in Figures 6 and 7. These graphs illustrate the high variability in stormwater N concentrations over time for a given site. Of particular note is the fact that for the New Haven sites (with the possible exception of Wheeler), the concentrations measured on the last two sample dates (2/24/10 and 3/29/10) were considerably lower than the previous 6 sample points. This may reflect seasonal changes in nitrogen sources, changes that the MS4 sampling program – with its annual sample frequency – will have a hard time picking up. (Of the 132 unique sample dates in the MS4 database, only 2 are in the months of January, February, or March.)

Due to the high temporal variability within sites, there were no significant differences among these 12 sites in NO_3 or TN concentrations (Kruskal-Wallis test, $p>0.05$).

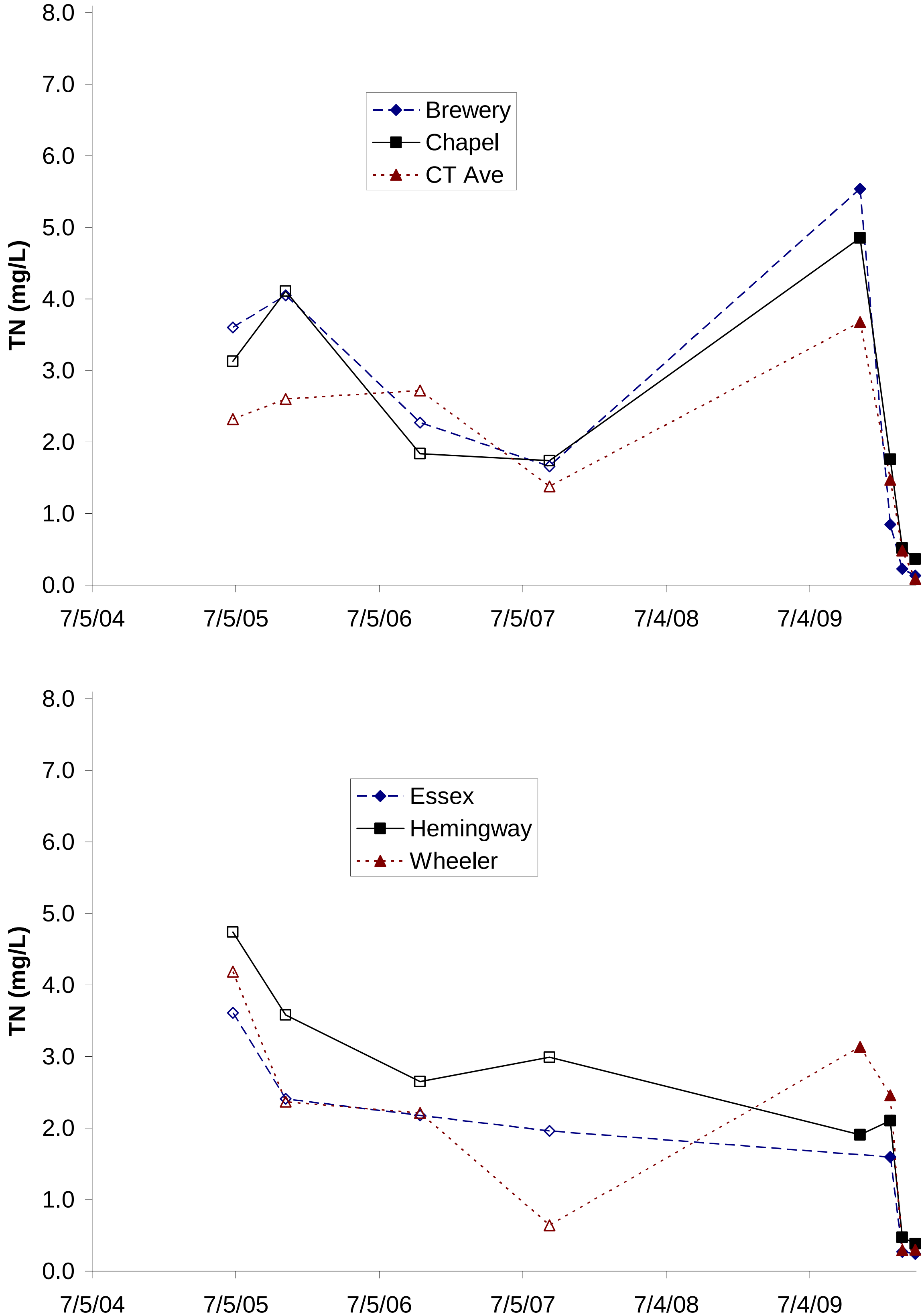
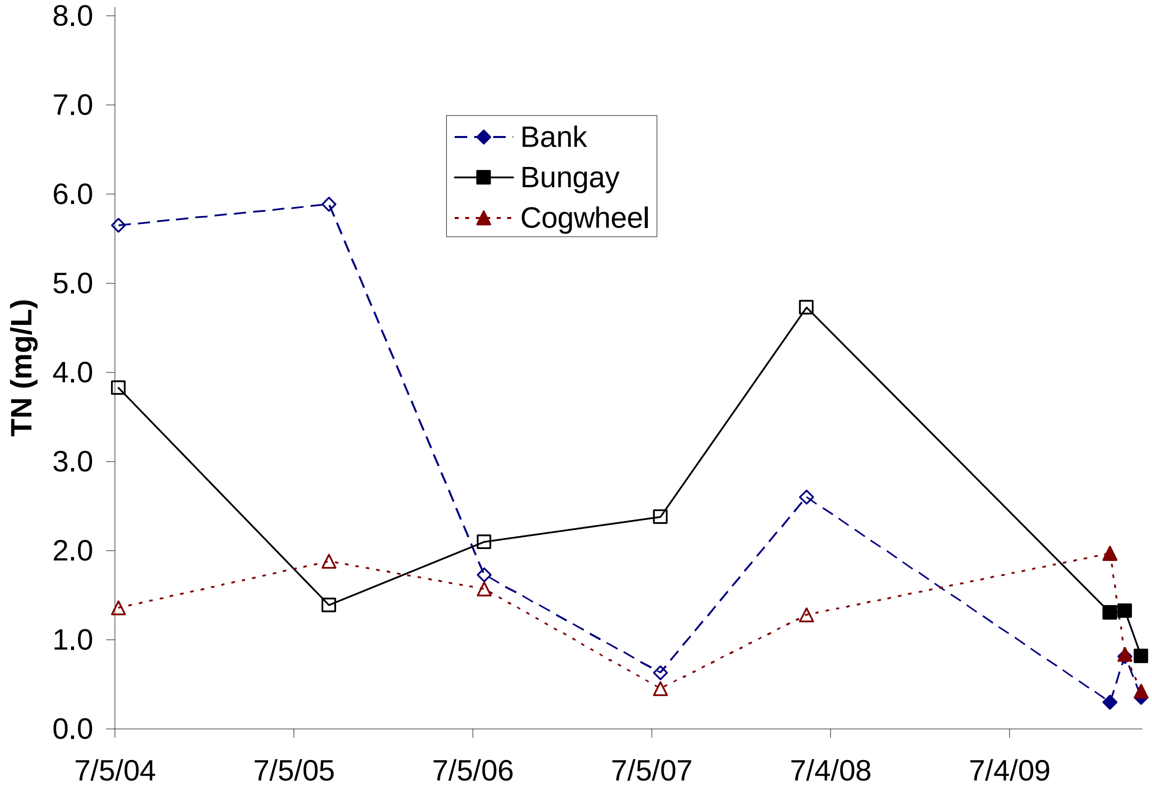


Figure 6. TN concentrations over time at the 6 New Haven stormwater sites. Open symbols indicate data from MS4 database; closed symbols indicate data collected for this project.



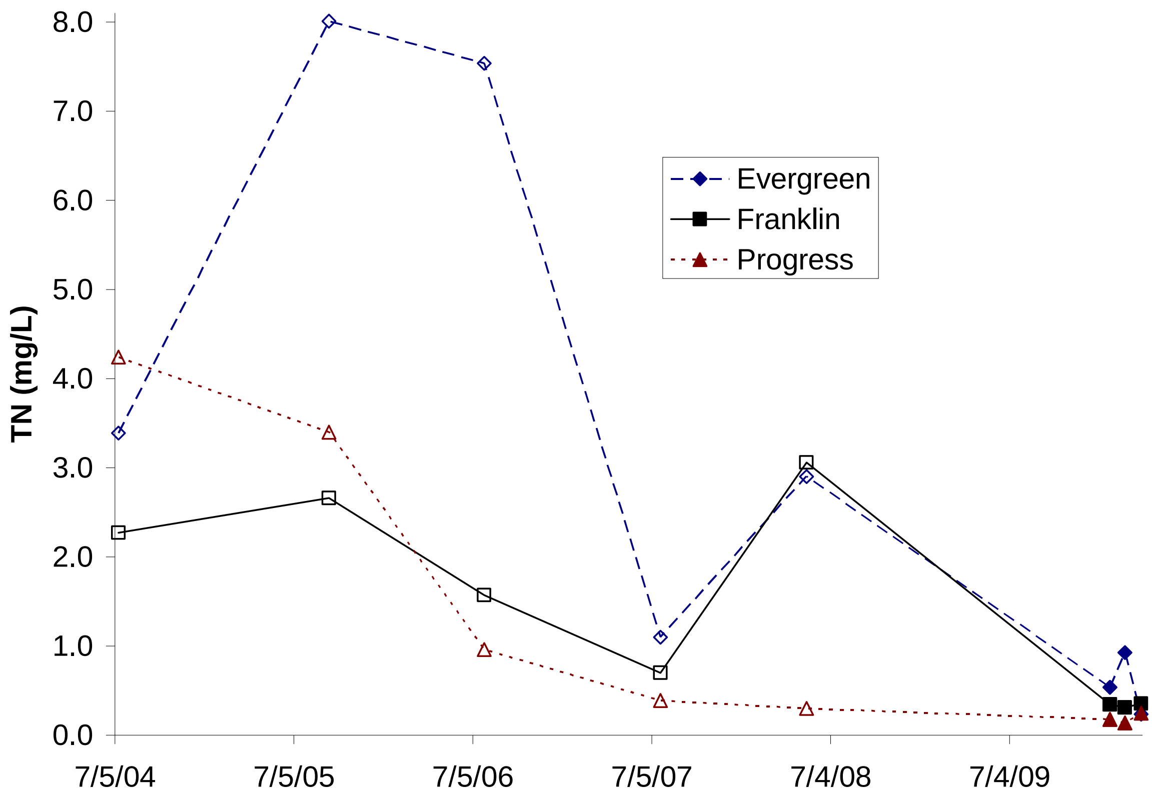


Figure 7. TN concentrations over time at the 6 Seymour stormwater sites. Open symbols indicate data from MS4 database; closed symbols indicate data collected for this project.

4.2. Stormwater Pond Sampling

4.2.1. Autosampler Storms

Water level, Cl, NO_3, and TN data at Lois for the three storms captured with the autosampler are shown in Figures 8-10. Several observations can be made:

- Storm 2 (11/30/09) was a considerably smaller event (precipitation 7mm; water level change ~0.04m) than storm 1 (11/20/09; precipitation 12 mm; water level change ~0.28m) and storm 3 (12/3/09; 23mm; ~0.65m).
- During storms 1 and 3, Cl concentrations in the effluent tracked Cl concentrations in the influent fairly closely, with a lag of up to 1 sample (30 minutes). In storm 2, in contrast, effluent Cl concentrations were considerably modulated from influent Cl levels (not as low at the beginning of the event, not as high towards the end of the event). This seems to indicate that in storm 2, the effluent represented a mix of pre-event and event water, while in the larger storms, the effluent was largely composed of event water that had spent a relatively short time in the pond.
- NO_3 concentrations in the effluent were generally reduced relative to concentrations in the influent. This reduction was largest in storm 2, presumably because of the longer residence time. However, even in storms 1 and 3, there appeared to be some NO_3 removal, especially near the beginning and end of the events.
- TN concentrations in storm 2 were very similar to NO_3 concentrations; apparently this small storm event led to very little sediment (and thus particulate N) delivery. During much of storms 1 and 3, TN concentrations were considerably higher than NO_3 concentrations, due to high sediment loads. TN removal – presumably driven primarily by settling of sediment – appeared to be quite efficient in storm 1, but much less efficient in the largest storm, storm 3.

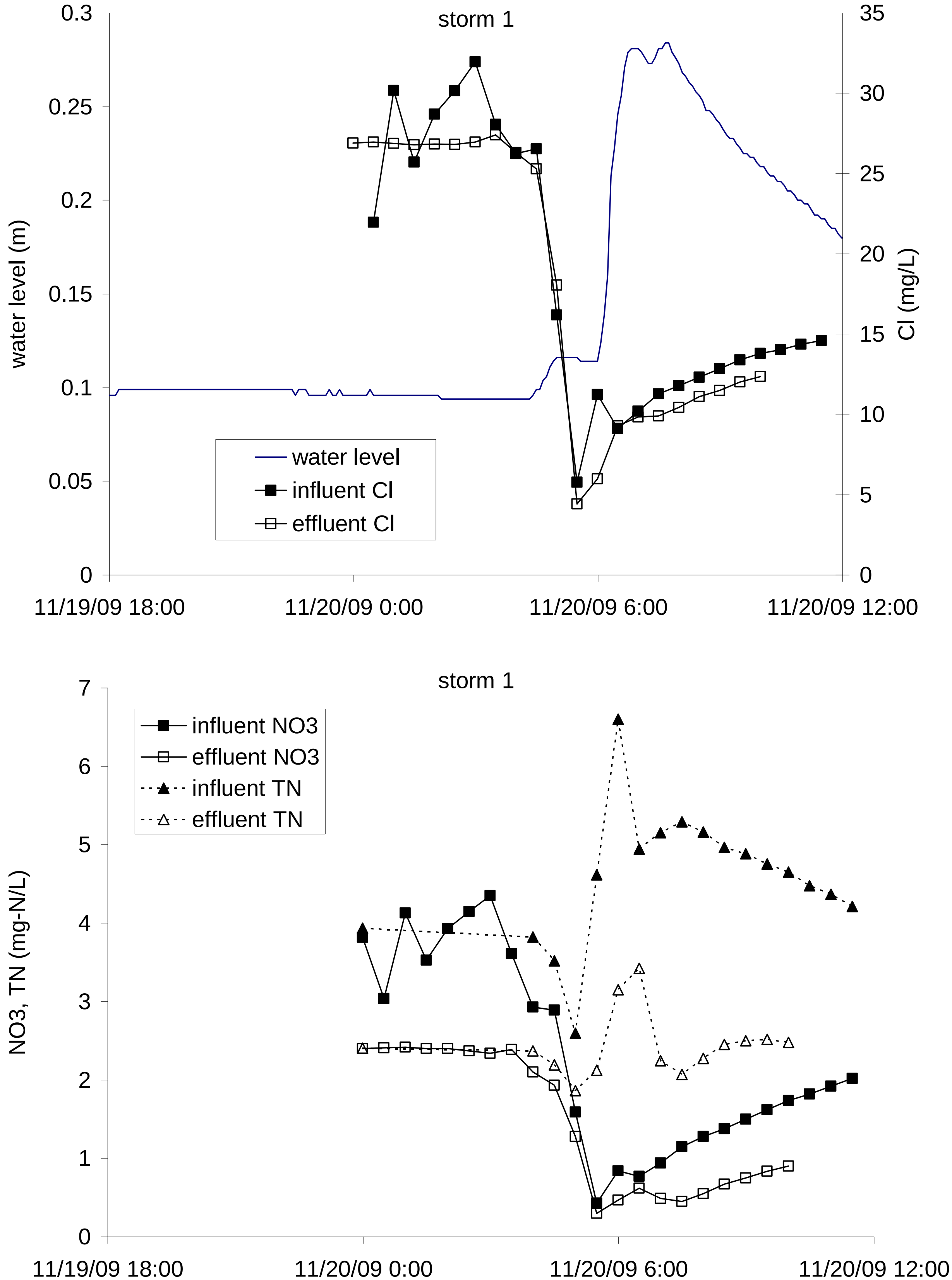


Figure 8. Water level and influent and effluent Cl, NO_3, and TN concentrations at the Lois pond over the course of storm 1 (precipitation = 12 mm; Figure 3). Samples collected with autosamplers.

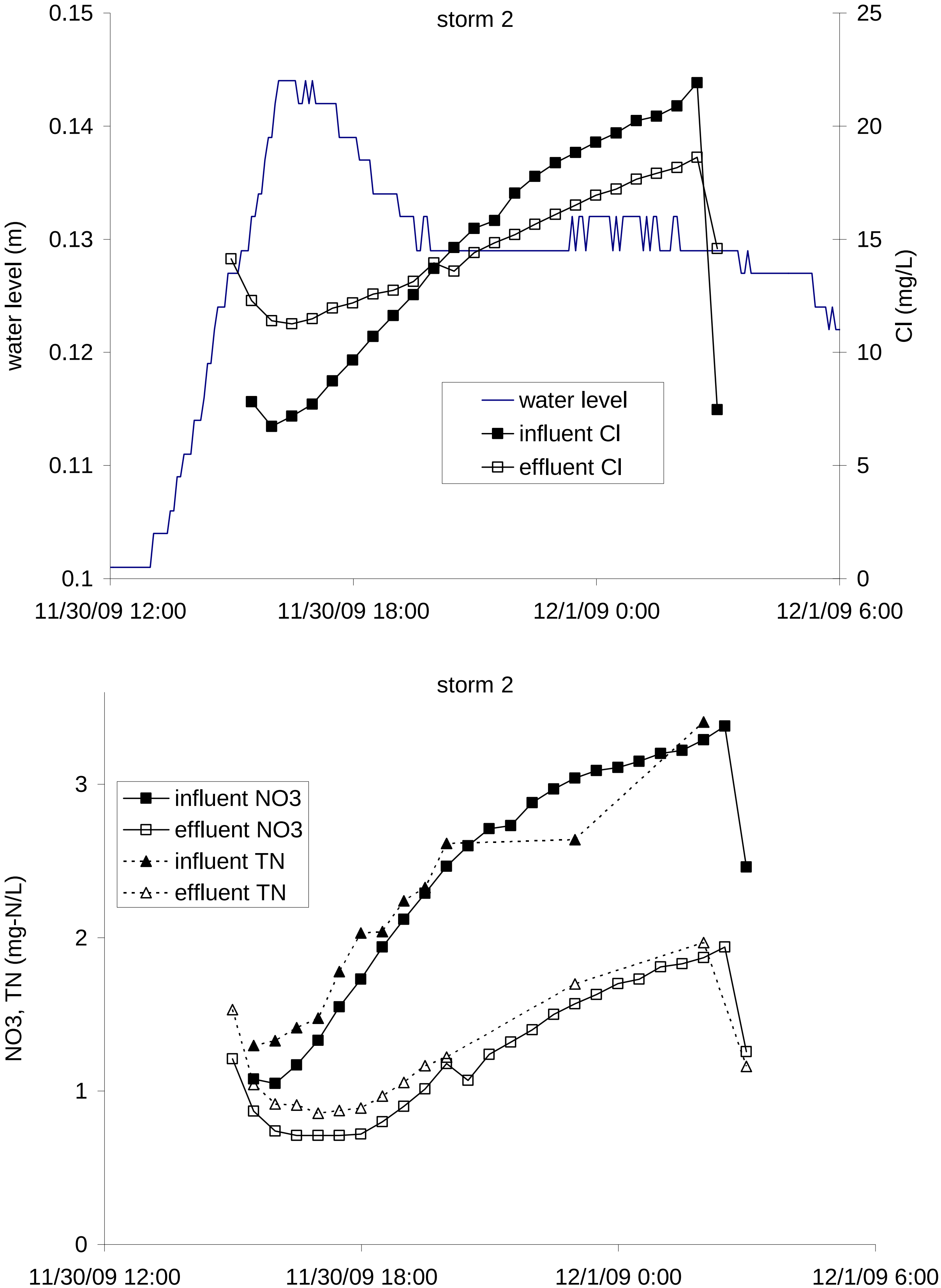
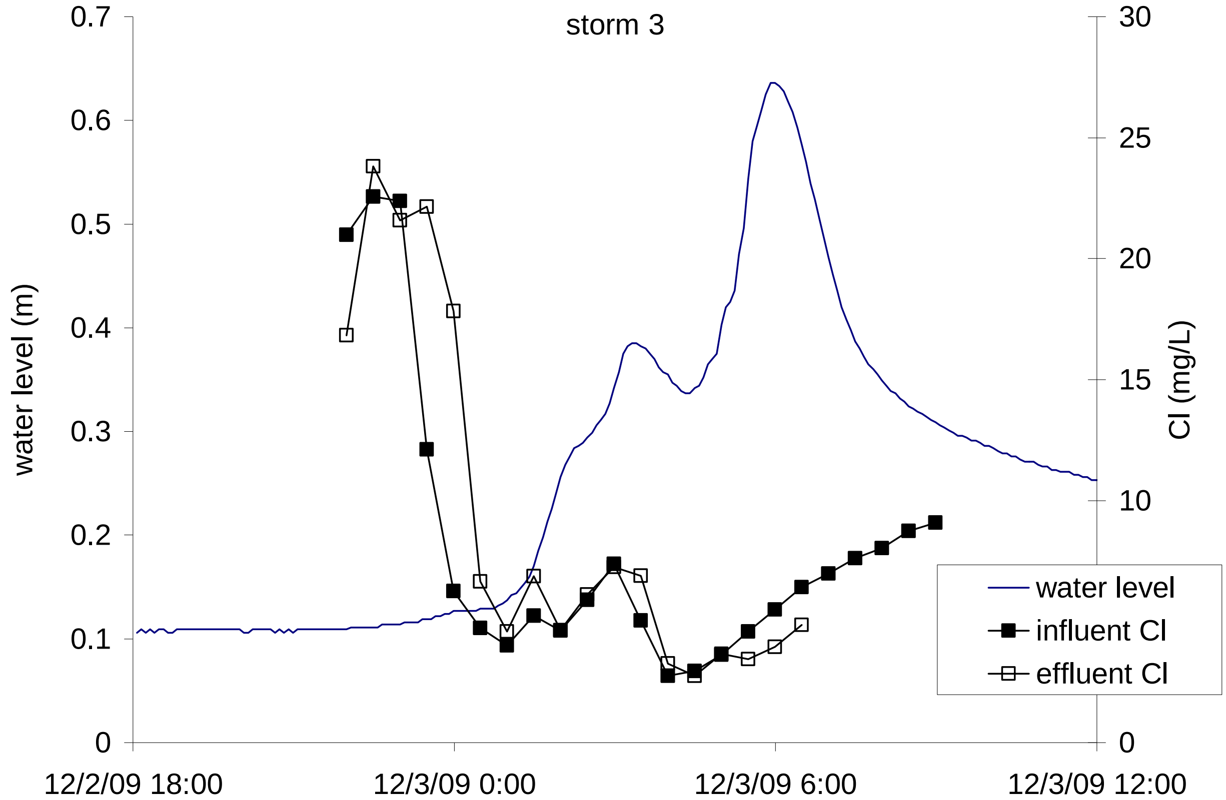


Figure 9. Water level and influent and effluent Cl, NO_3, and TN concentrations at the Lois pond over the course of storm 2 (precipitation =7 mm; Figure 3). Samples collected with autosamplers.



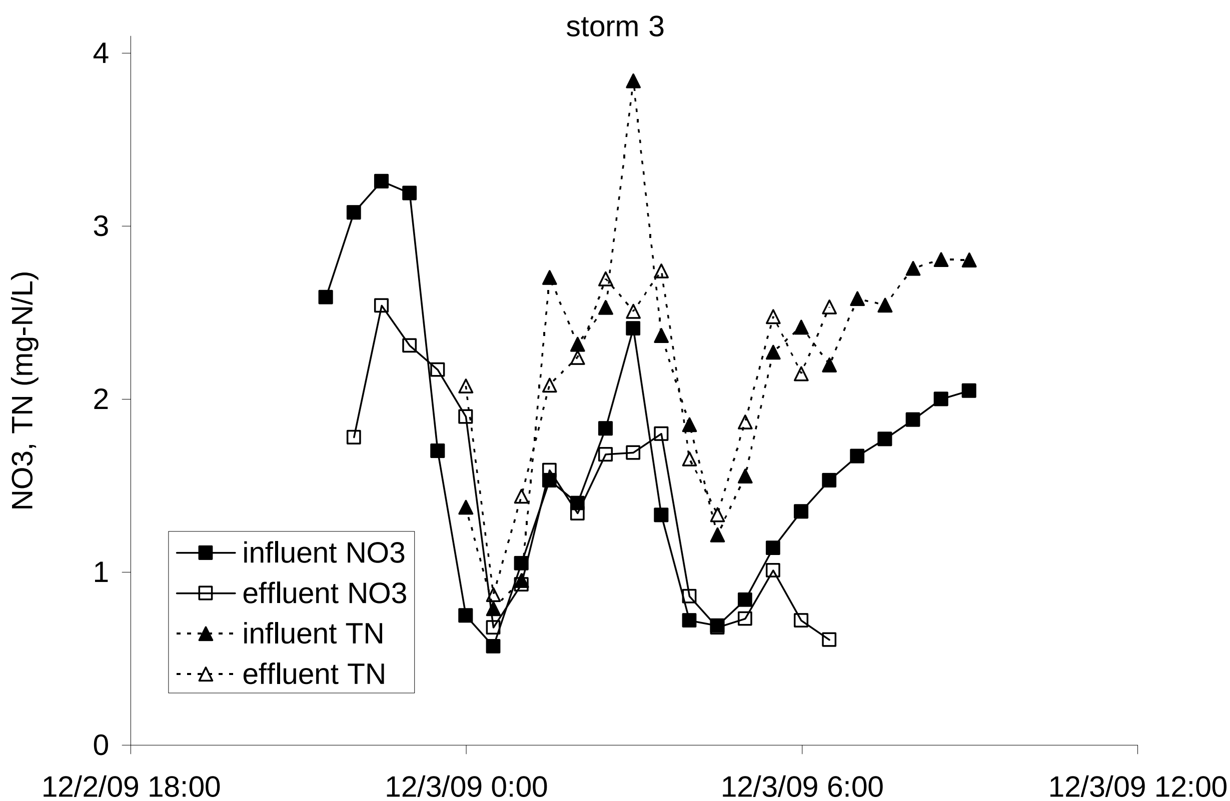


Figure 10. Water level and influent and effluent Cl, NO_3, and TN concentrations at the Lois pond over the course of storm 3 (precipitation =23 mm; Figure 3). Samples collected with autosamplers.

4.2.2. Stormwater Pond Manual Sampling

Water levels and total nitrogen concentrations (influent and effluent) over time for each site are shown in Figures 11-14. In terms of hydrologic regime, most sites showed a pattern of rapid increases in water level during storm events, followed by rapid return to a baseline water level. This fill-drain pattern at most sites occurs over a ~2-12 hour period, depending on the rain event. Sites that appear to drain a little more slowly include Thornton, Mather, and the upper pond at Davis. St. Johns shows two distinct baseline levels, with a rapid drop from the upper to the lower level; the reason for this behavior is unknown.

TN concentrations vary widely both within and between sites. Cursory comparison of influent and effluent concentrations suggests that Branford, Davis, Lois, and Mather appeared to have the most consistent removal of TN.

Probability plots of EMCs for Cl, NO_3, and TN for each site[4] are shown in Figures 15-17. Also indicated on these plots are the results of paired t-tests comparing influent and effluent concentrations.

As can be seen in Figures 15-17, nitrogen removal efficiency varied by site. Davis, Lois, and Mather all showed highly significant removal for both NO_3 and TN, while St. John showed removal for TN but not NO_3. The remaining 3 sites (Elderslie, Lowes, and Thornton) showed no indications of nitrogen removal. For the sites with significant removal, overall removal efficiencies ranged from 35% to 65% for NO_3 and from 29% to 44% for TN.

Nitrogen removal efficiency was concentration-dependent for several of the sites. Specifically, for 3 out of the 4 sites with significant N removal (all but Mather), TN removal was effective at high concentrations but not at low concentrations. This is indicated in Figures 15-17 by influent and effluent lines that cross at low concentrations but diverge at high concentrations. It is important to note that the irreducible concentrations at these sites (as indicated by the concentrations at which the lines cross) are all below 1 mg/L TN. NO_3 removal may be less concentration-dependent, as only Davis showed such a pattern for NO_3 (Figures 15-17).

We expected influent and effluent Cl concentrations to be indistinguishable. However, we found that effluent Cl concentrations were significantly higher than influent concentrations for 3 of our sites. For Lois and Lowes, these differences were relatively small and may be explained by data variability and particularly by the imperfect fit of the data to a log-normal distribution. However, for Mather, differences were very large, especially at higher concentrations, where effluent Cl levels were ~20-80 times as high as influent Cl levels. This phenomenon has been observed at this site by others (Gabe Benoit, personal communication), and seems to indicate the presence of Cl-contaminated groundwater (perhaps due to road salting) which seeps into the pond in between storm events, leading to high Cl concentrations in the pond relative to the influent stormwater. An alternative conservative tracer, SO4, showed no significant difference between influent and effluent.

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[4] Branford was excluded from this analysis, since we had data for only 3 storms from that site.

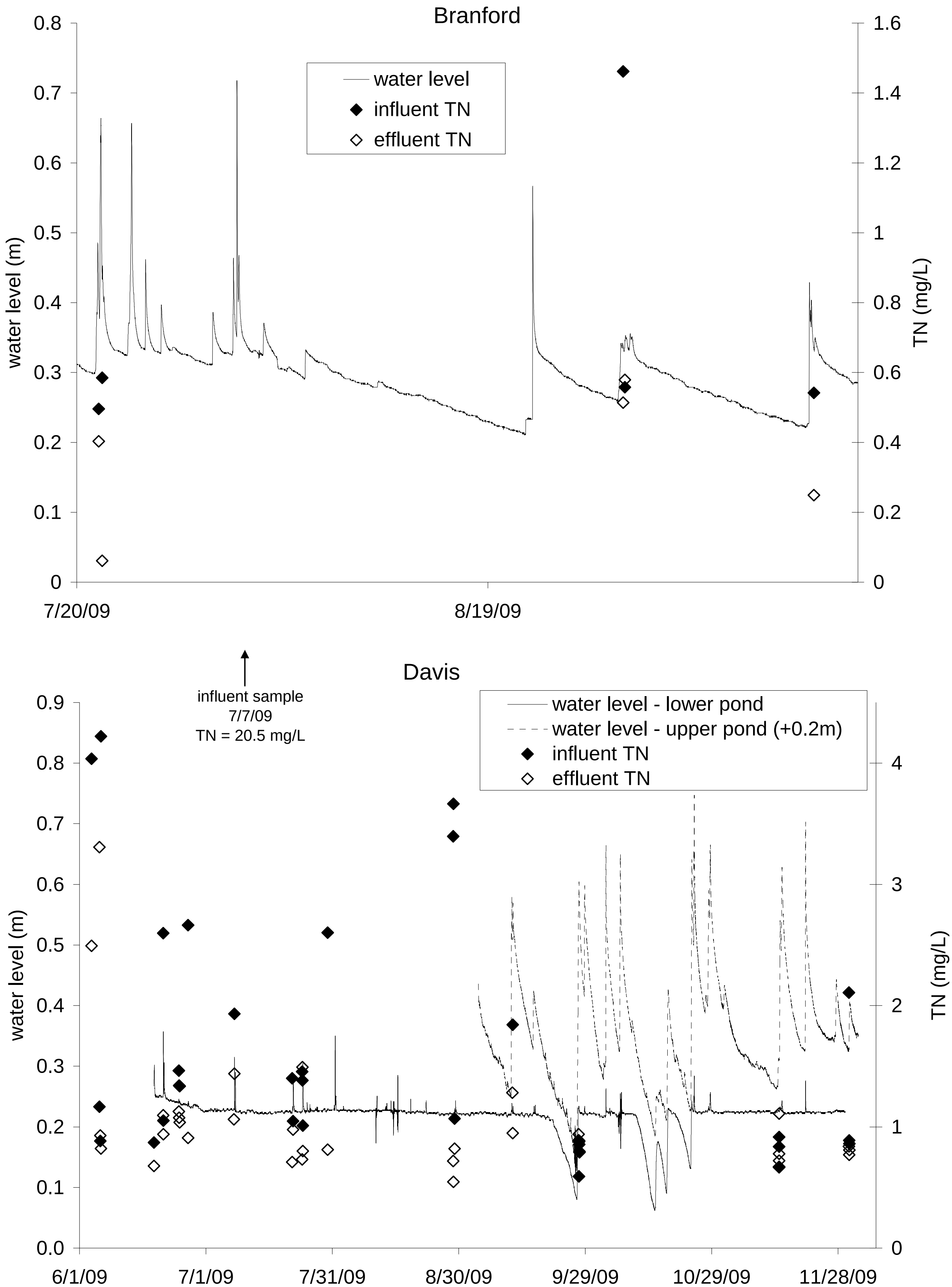
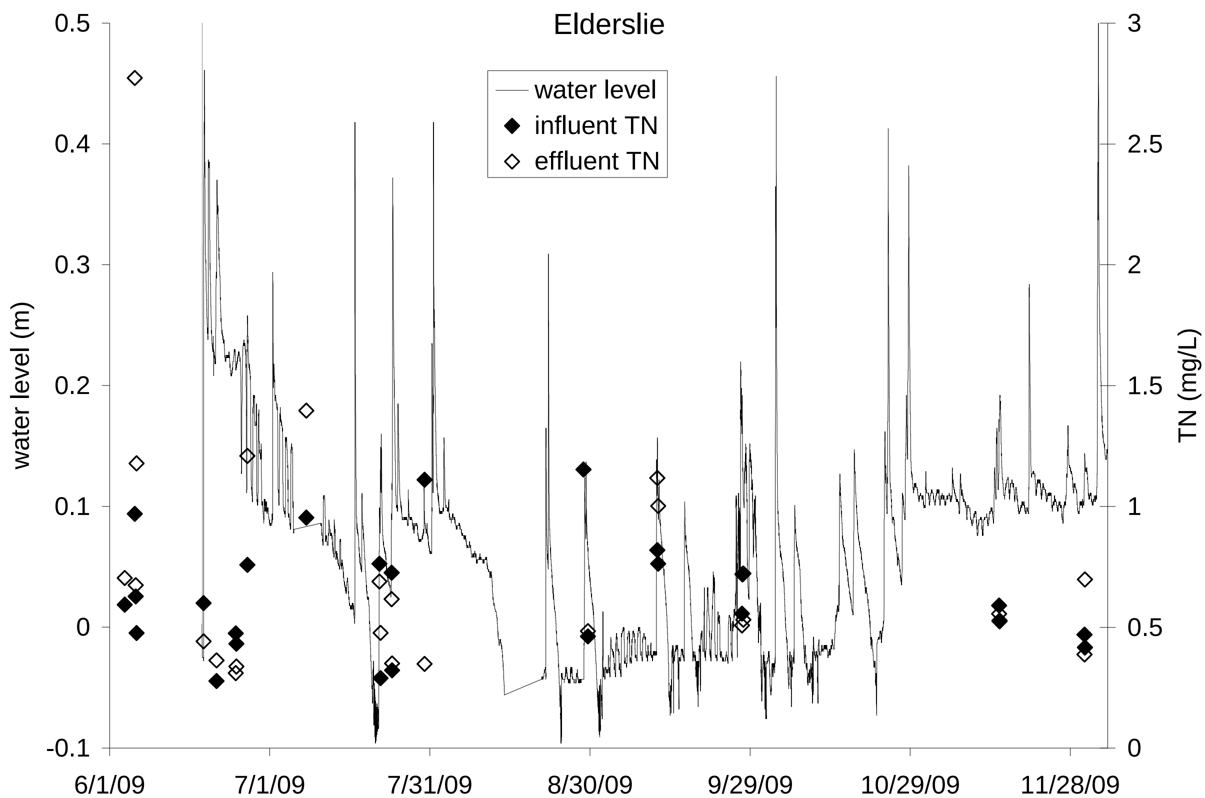


Figure 11. Water level (left axis) and influent and effluent TN concentrations (right axis) for all samples collected at Branford (top) and Davis (bottom) stormwater ponds.



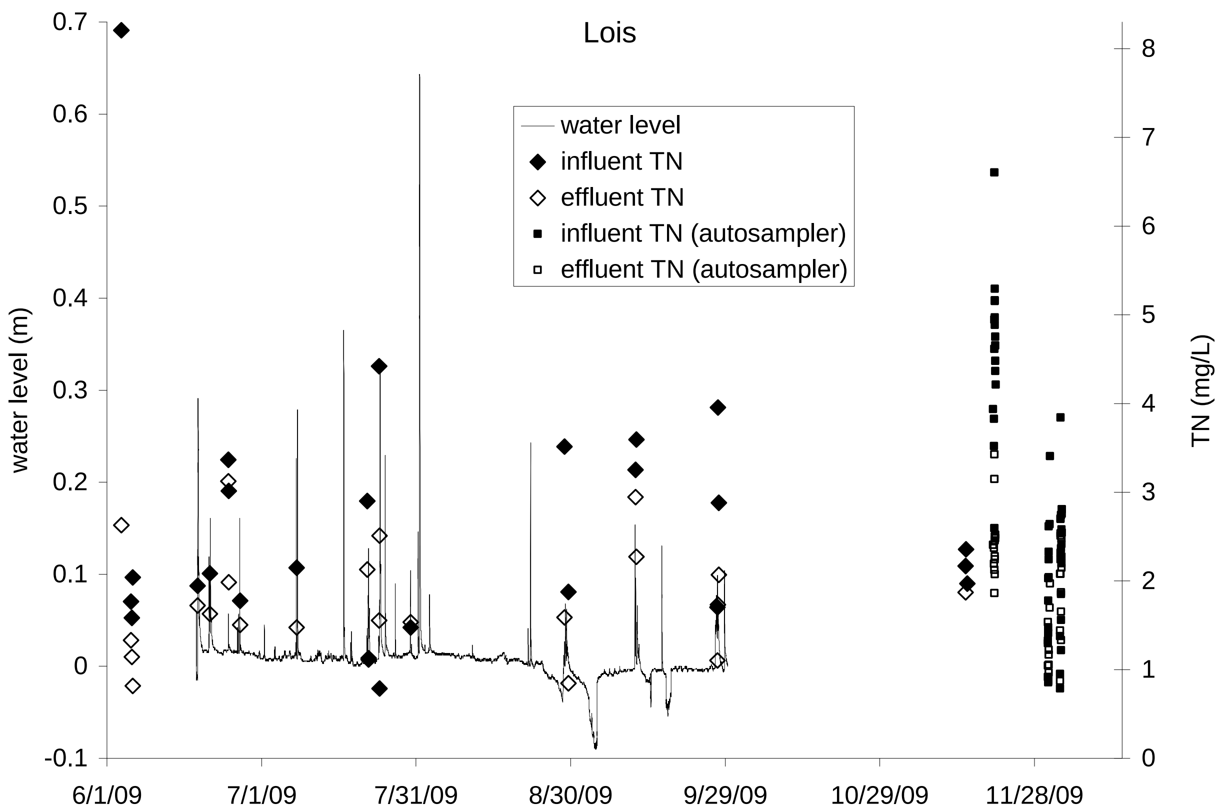


Figure 12. Water level (left axis) and influent and effluent TN concentrations (right axis) for all samples collected at Elderslie (top) and Lois (bottom) stormwater ponds.

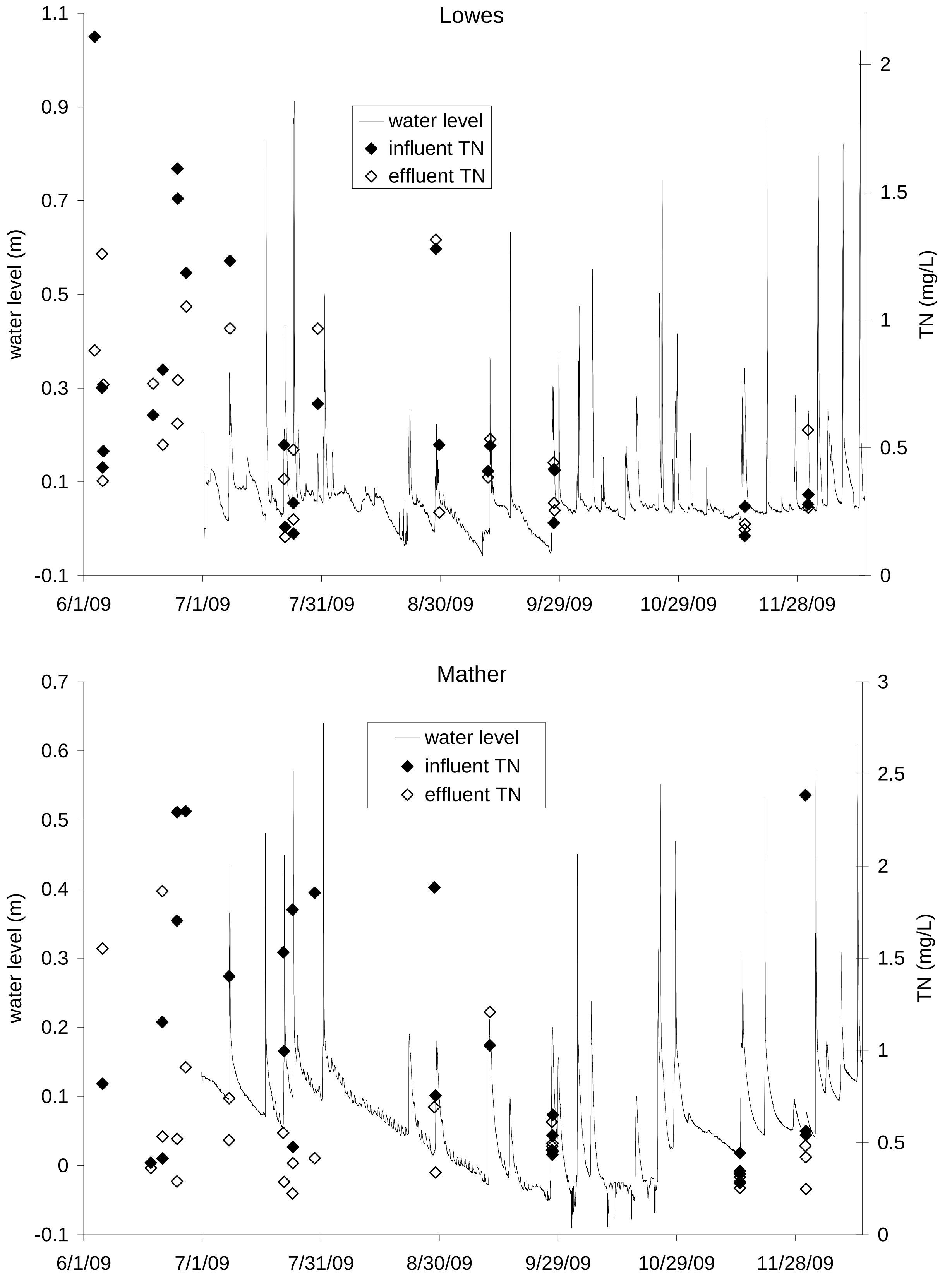


Figure 12. Water level (left axis) and influent and effluent TN concentrations (right axis) for all samples collected at Lowes (top) and Mather (bottom) stormwater ponds.

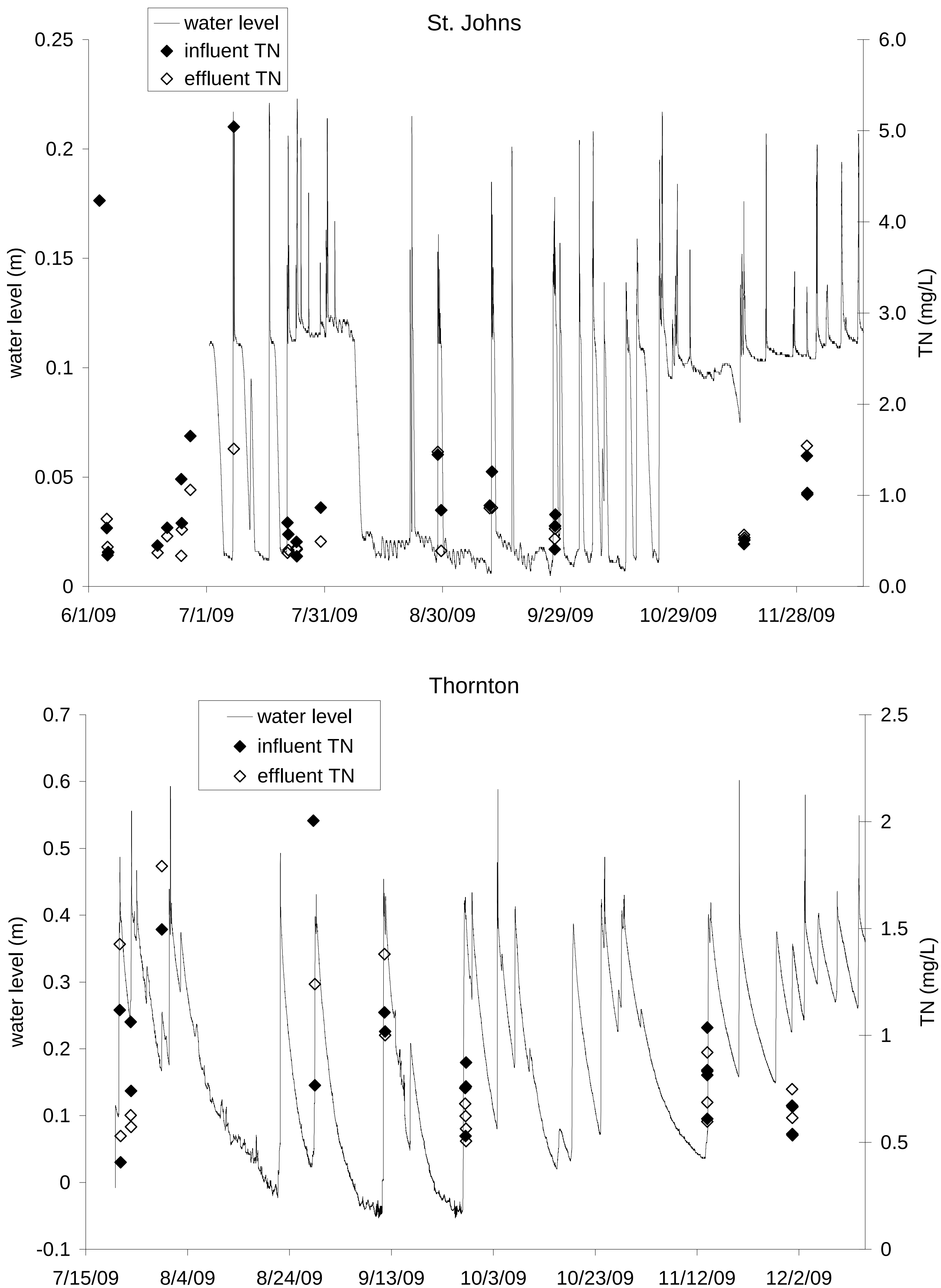


Figure 14. Water level (left axis) and influent and effluent TN concentrations (right axis) for all samples collected at St. John (top) and Thornton (bottom) stormwater ponds.

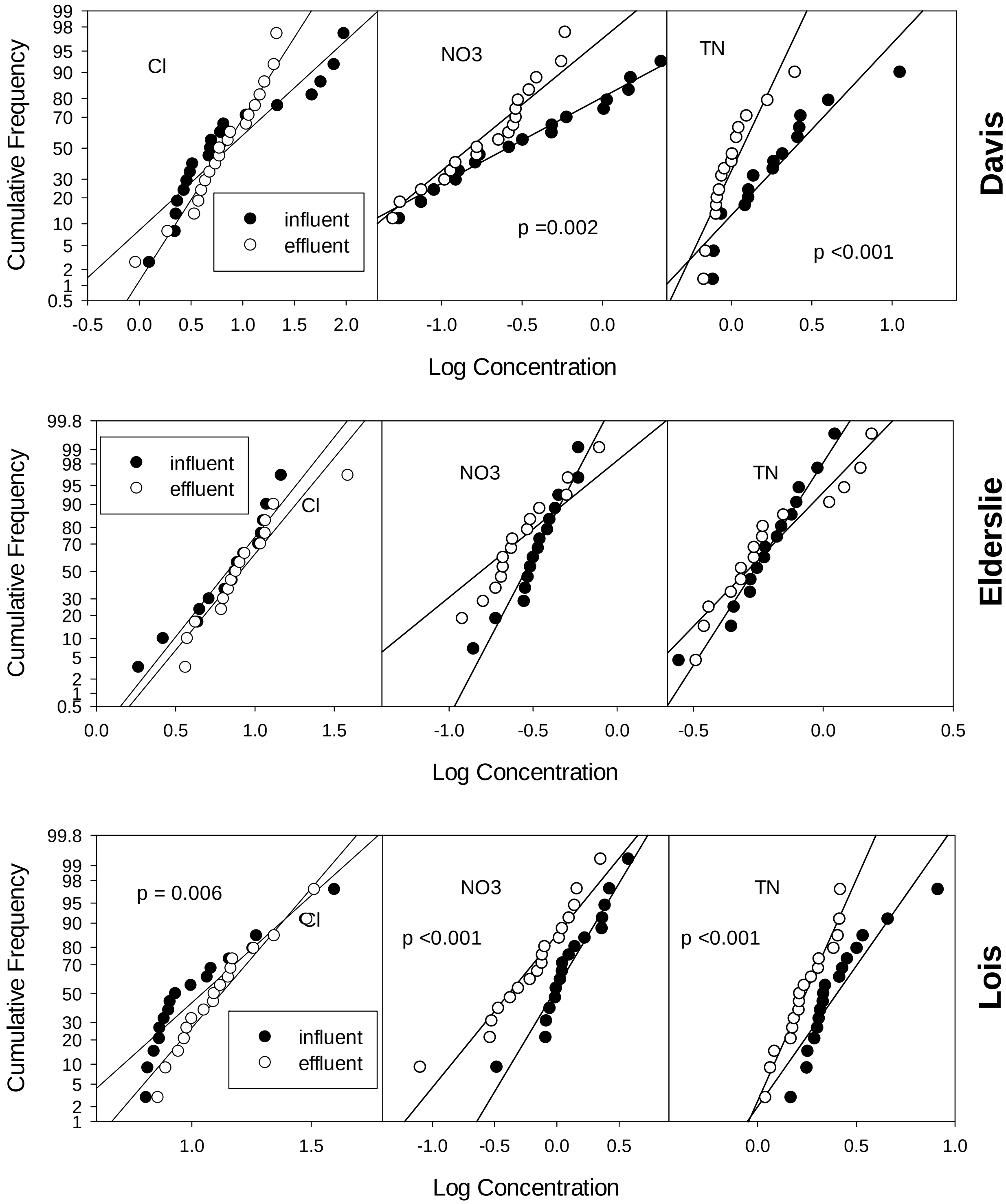


Figure 15. Probability plots of influent and effluent Cl, NO_3, and TN concentrations at Davis, Elderslie, and Lois stormwater ponds. Each dot represents the EMC over one storm event. All concentrations were log transformed before plotting. P values shown are for paired t-test (or, where log-transformed values are not normally distributed, Wilcoxon Signed Rank Test).

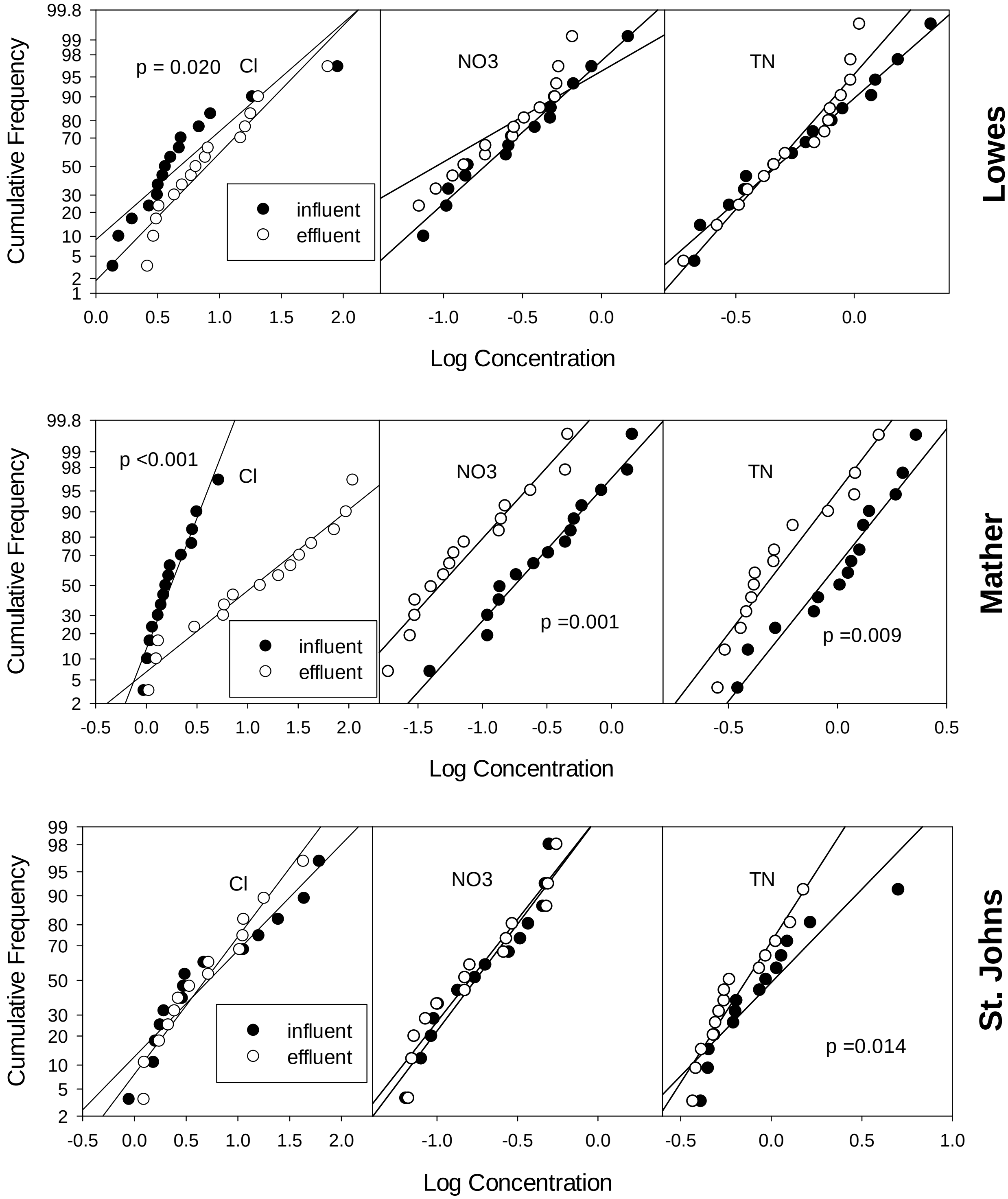


Figure 16. Probability plots of influent and effluent Cl, NO_3, and TN concentrations at Lowes, Mather, and St. John stormwater ponds. Each dot represents the EMC over one storm event. All concentrations were log transformed before plotting. P values shown are for paired t-test (or, where log-transformed values are not normally distributed, Wilcoxon Signed Rank Test).

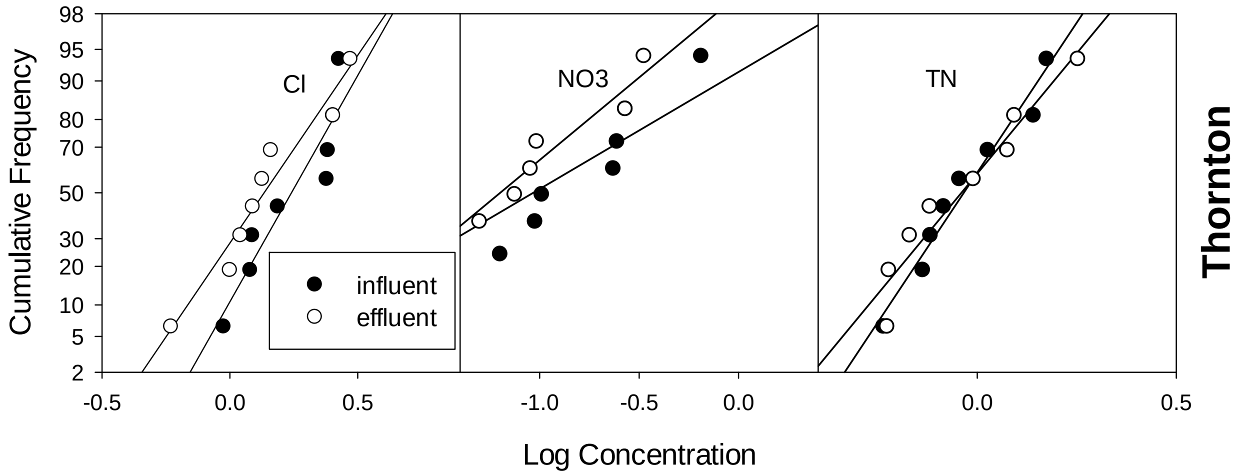


Figure 17. Probability plots of influent and effluent Cl, NO_3, and TN concentrations at Thornton stormwater pond. Each dot represents the EMC over one storm event. All concentrations were log transformed before plotting. P values shown are for paired t-test (or, where log-transformed values are not normally distributed, Signed Rank Test).

The differences in TN removal between sites may be explained, at least in part, by differences in influent nitrogen loads. The four sites with significant TN removal all had higher mean influent TN concentrations than the three sites with no significant TN removal (Figure 18). The threshold for effective TN removal appears to be somewhere around 1 mg/L TN (mean influent concentration). Once this threshold was exceeded, there was no real difference in removal efficiency between the sites with concentrations of ~1.2 mg/L (Mather and St. Johns) and those with concentrations of ~2.5 mg/L (Davis and Lois) – although, as noted above, storm-to-storm variations in influent TN concentration at these sites did lead to variations in efficiency.

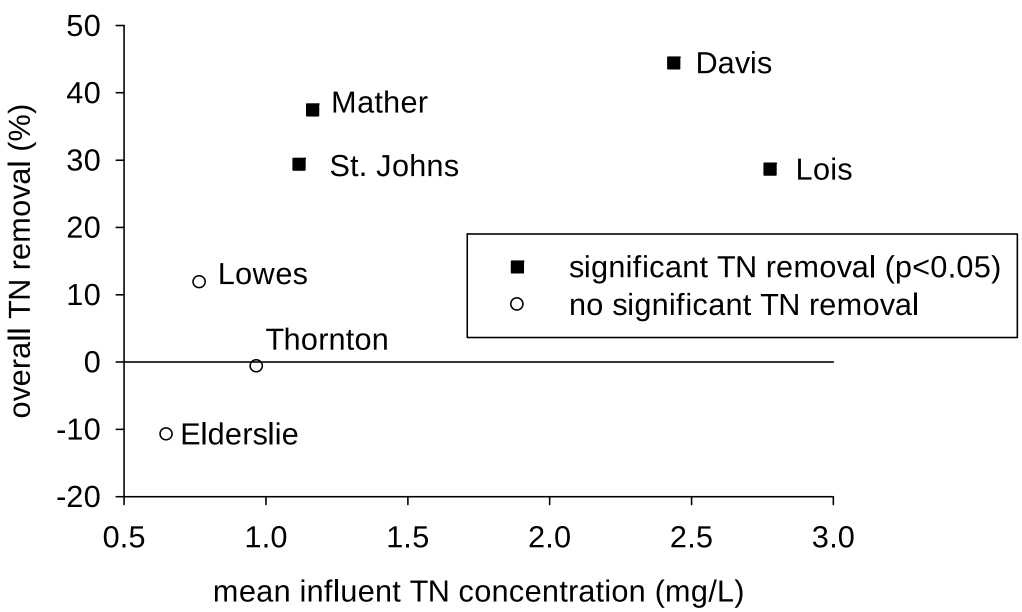


Figure 18. Overall TN removal by site as a function of mean influent TN concentration. Overall TN removal is calculated as the weighted average of all sampled storms (see Section 3.2.4). Solid squares indicate sites with significant TN removal (paired t-test), while open circles indicate sites without significant TN removal.

5. Discussion

The discussion below addresses each hypothesis in turn, and then discusses next steps.

5.1. Hypothesis 1.

H_1:Untreated municipal stormwater in Connecticut generally has relatively low TN concentrations of ~2 mg/L, but a substantial fraction of sites have higher concentrations.

Our analysis of the MS4 database indicates that median TN concentrations in CT stormwater are approximately 1.6 mg/L, but that some sites have concentrations that are significantly higher than other sites ($p<0.001$; Figure 4). The most polluted sites in the MS4 database account for a substantial fraction of the total N load from all sites (Figure 5).

However, our more detailed sampling of 12 sites indicates that temporal variability within sites is probably larger than indicated by the MS4 database, since that database is characterized by an annual sampling frequency (maximum n of 5 per site) and an undersampling of winter months. Thus, our conclusion that there are truly high-concentration sites rests on a weak foundation.

We thus consider hypothesis 1 to be tentatively affirmed.

5.2. Hypothesis 2.

H_2: Stormwater BMPs in Connecticut (specifically wet ponds) are able to achieve statistically significant reductions in TN loads when influent concentrations are high, but not when they are low.

Of the 7 ponds examined in detail, the 4 ponds with highest TN concentrations were able to achieve statistically significant reductions in TN loads, while the 3 ponds with lowest TN concentrations were not. At 3 of the 4 successful ponds, removal was a function of concentration. We estimate the irreducible concentration to be ~1 mg/L, lower than previous estimates. Overall removal for the 4 successful ponds for the storms studied was about 35%.

We thus consider hypothesis 2 to be largely affirmed.

5.3. Hypothesis 3.

H_3: The target of 10% reduction in stormwater TN loads can be achieved by selective application of BMPs to the most polluted sites.

Figure 5 can be used, together with our BMP efficiency data, to assess our ability to achieve the target of 10% reduction in stormwater TN. If BMPs were targeted towards the most polluted sites, we would need to target the top 30% of the TN load in order to achieve a 10% overall reduction (assuming that since we are applying BMPs to polluted sites, they will achieve the 35% overall reduction averaged by the 4 highest-concentration sites in our study). Figure 5 illustrates that this corresponds to roughly the top 15% of sites.

Thus, hypothesis 3 is affirmed. We predict that a 10% reduction in stormwater TN could be achieved by applying stormwater ponds to 15% of the stormwater in CT - as long as this stormwater was from the most polluted sites.

Several important caveats apply:

- As noted above, our conclusion that high-N sites exist is based on the MS4 database, with its limited sampling window. Further testing may demonstrate that when a fuller temporal picture is available, sites are really quite similar overall, which would prevent us from targeting BMPs towards more polluted sites.
- Our calculations assume an overall TN reduction of 35% from stormwater ponds. While our data suggest that this is likely to be reasonable for sites with mean TN concentrations >1 mg/L, our results are based on a relatively small sample size and narrow concentration range.
- We have assumed that the MS4 database accurately represents stormwater in CT, and that the sites included in the database each produce equal volumes of stormwater. If the more polluted sites tend to be smaller, then the top 15% of sites would represent less than 15% of the stormwater flow (and less than 30% of the TN), and a 10% reduction could not be achieved with these sites.
- We have assumed that BMPs could actually be applied to the most polluted 15% of sites. In reality, two problems would prevent this from happening:
    - Not all sites are amenable to pond placement. Many of the most polluted sites may not have sufficient land available to construct a stormwater pond.
    - It is difficult to identify the most polluted sites. Even sites that are included in the MS4 database are not well enough understood; this is even more true for the majority of stormwater outfalls in CT, where no samples have been taken.
- Our calculations are aiming for a 10% reduction from current conditions, assuming no further development. In reality, ongoing land development continues to increase the volume of stormwater and the load of stormwater N that must be addressed.

5.4. Next Steps

Our results suggest several further steps to improve our understanding of the ability of BMPs to control stormwater nitrogen in Connecticut:

- *continue and expand stormwater monitoring*: The MS4 database has provided us with a valuable picture of stormwater in Connecticut, and has allowed us to begin addressing the question of spatial variability in nitrogen concentrations. It is critical to continue building this database. Municipalities should be encouraged to sample the same sites from year to year, rather than changing sample sites. In addition, it would be extremely useful to collect additional samples in different times of year to supplement the samples collected by the municipalities. Sites targeted for additional sampling should include both high-nitrogen and average-nitrogen sites to determine if the patterns deduced from the current database hold up to further scrutiny. Table 9 provides the list of the top 10% of sites from the MS4 database (from the 221 sites which have 5 samples each); several of these should be targeted for additional sampling.

Table 9. List of the top 22 sites by median TN concentration (out of the 221 sites with 5 samples per site)

Anisfeld ID#	median TN (mg/L)	town	type of site	location description
107	7.17	Danbury	Commercial	Station 6
474	6.16	Old Lyme	Residential	Maple Ave and Groton Ave
613	6.15	Stratford	Industrial	Garfield Ave
621	4.34	Suffield	Residential	(R-1) outfall in rip-rap S of Grassman Pond Lane
663	4.3	Vernon	Residential	Sample R-3 N41.83343,W72.49098 (NAD 83)
464	4.1	Norwich	Commercial	41°33'05"/72°06'33" (SP3)
590	4.1	Southbury	Industrial	outfall 5 Oak Tree Rd, 18"corrugated metal outfall adj to package store
496	4.06	Plainville	Residential	R2-outfall into Quinnipiac River behind centerfield of eastern-most field @ Trinity Sports Complex @ Trumbull Park @ end of Linsley Dr
126	4.02	Derby	Commercial	C2 41 19' 10.18"N, 73 3' 25.18"W
661	3.9	Vernon	Industrial	Sample I-1 N41.86593,W72.46278 (NAD 83)
616	3.84	Stratford	Residential	Monroe St
105	3.81	Cromwell	Residential	1021500/788150 Easting/Northing Court Street
129	3.76	Derby	Residential	R1 41 19 6.52 N , 73 4 16.69 W
385	3.56	Milford	Residential	Mayflower Dr E of Wayland lat 41 12'34" long 73 04'06"
392	3.43	Montville	Industrial	I 400 Maple Ave (41 26' 38"N 72 07'22"W) "D&W Transport"
104	3.37	Cromwell	Industrial	1027480/779860 Easting/Northing New Lane
615	3.37	Stratford	Residential	Intersection of Park & Maple St
404	3.29	Naugatuck	Residential	R2 Aetna Street; Galpin St to Long Meadow Brook
102	3.28	Cromwell	Commercial	1019370/779930 Easting/Northing Stop & Shop
384	3.25	Milford	Residential	929 Naugatuck Ave lat 41 12'51" long 73 06'16"
659	3.21	Vernon	Commercial	Sample C-5 N41.82893,W72.49788 (NAD 83)
593	3.2	Southbury	Residential	outfall 2 Wheeler Rd N of intersection with East Hill Road

- *conduct follow-up studies on BMP effectiveness*: The results reported here on BMP N removal must be considered preliminary, due to the limited spatial and temporal scope of this project. The 8 ponds studied constitute only a small fraction of the population of stormwater ponds in Connecticut. More importantly, the short-term nature of this study makes it hard to draw firm conclusions. In addition, we were not able to include flow measurements in this study, a shortcoming that limits our ability to fully understand N loads. We recommend that follow-up studies be conducted that would include flow measurements, extend over a longer time period, and possibly target more ponds with high influent N concentrations. This will help confirm our results and provide greater understanding of the factors controlling N removal, as well as a better ability to predict the amount of N removal that can be expected from new BMPs.

- *evaluate the feasibility of targeting high-nitrogen sites*: Our results suggest that the most effective way to reach the 10% reduction goal will be to target high-nitrogen sites for BMP retrofitting. However, as noted above, the logistics of this approach may prove difficult. We recommend a preliminary evaluation of the technical, financial, and political feasibility of installing BMPs at the sites listed in Table 9.

6. Conclusions

Our data and analysis suggest two primary results:
(a) there are stormwater sites in Connecticut with consistently high N concentrations
(b) stormwater ponds can be effective at removing nitrogen when influent nitrogen concentrations are high.

Putting these two results together leads to the conclusion that applying BMPs to high-nitrogen stormwater is a viable strategy for reducing N loads to LIS, both because it is a way to address a substantial fraction of the N load in a limited number of sites and because those ponds are more likely to be effective. In contrast, applying BMPs indiscriminately is likely to result in resources wasted on ponds that are receiving low loads of nitrogen and that are ineffective at removing it.

However, it is important to caution that each of the results outlined above – and thus the conclusions drawn from them – should be considered preliminary, due to the methodological difficulties of addressing these questions and the limited scope of this project.

7. Acknowledgments

Julie Goodness carried out the bulk of this project as her MESc work at Yale FES. She put in many long, rainy hours in the field and many equally long but drier hours in the lab and in front of the computer. I am very grateful to her for her hard work.

Julie was ably assisted by several other Yale FES students in various aspects of the field work, including Saalem Adera, Manuel Mavila, and Norio Takaki. Rudresh Sugam of The Energy and Resources Institute (TERI) in India assisted with lab work and data analysis. Saalem Adera identified the MS4 sampling locations and collected the stormwater samples; Nathan Karres assisted in early aspects of that work. Torrance Hanley and Elizabeth Hatton graciously ran one batch of the stormwater samples for TNTP. Thanks to all of them.

Jonas Karosas and Helmut Ernstberger provided invaluable assistance to this work by training and supervising students in the lab. Professors Gaboury Benoit and David Skelly contributed helpful comments on study design.

Many people throughout Connecticut generously shared their time and expertise to help us identify and understand stormwater and BMP sites, including: R. Scott Allen of the Town of Orange; Joseph Bragaw of the Town of Stonington; Terry Gilbertson, Gerry Shaw, and Kristine Sullivan of the Town of Woodbridge; Wendy Goodfriend of the Connecticut River Coastal Conservation District; John Hudak of the South Central Connecticut Regional Water Authority; Jim MacBroom of Milone and MacBroom; Azalea Mitch of the New Haven Water Pollution Control Authority; Nisha Patel and Paul Stacey of the CT Department of Environmental Protection (CT DEP); Diana Ross of the Town of Branford; and Larry Secore of Nafis and Young Engineers Inc. Carol Papp of CT DEP provided us with the MS4 database.

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